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NONLINEAR TEMPORAL INTERACTIONS IN CLICK-EVOKED OTOACOUSTIC EMISSIONS

Sarosh Kapadia, BEng, MEng

A thesis submitted in partial fulfilment of the requirements of the
Open University for the degree of Doctor of Philosophy

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MRC Institute of Hearing Research



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**To Robyn, Sam and Sarah, for time that should have been spent with them,
and to my mother Gool**

ABSTRACT

Click-evoked otoacoustic emissions (CEOAEs) may be reduced in amplitude by the presentation of “suppressor” clicks that either closely lead or follow the stimulus (“test”) clicks. This “click suppression” represents nonlinear temporal interaction between the test and suppressor clicks and/or the CEOAEs they evoke. Such suppression has not previously been studied in detail and the mechanisms giving rise to it are not understood. In particular, it is unclear whether click suppression may simply reflect the compressive nonlinearity of the CEOAE level function. It is also unclear whether the larger magnitude “rate suppression” observed in CEOAEs measured using streams of clicks at very high rates may be explained by a simple additive accumulation of click suppression.

The present study addresses these questions by detailed measurement of this suppression phenomenon in 20 normal adult ears, and establishes that:

1. Maximum suppression is generally obtained for suppressors presented up to 4 ms *in advance* of test clicks, contrary to expectation.
2. Suppression by suppressors that lead test clicks does not simply reflect CEOAE level function nonlinearity. It may, instead, arise from disturbance of the generator elements from their resting state prior to generation of the CEOAE.
3. Suppression by following suppressors behaves markedly differently from that by leading suppressors, and appears more closely related to level function nonlinearity.

4. Contrary to previous suggestions, suppression for both leading and following suppressors is insensitive to polarities of test and suppressor clicks.
5. Suppression does not accumulate in a simple, additive manner as has previously been suggested. Consequently, a more complex mechanism underpins the greater magnitude of rate suppression.

The parametric characterisation of click suppression presented may form the basis of models to explain this little-studied phenomenon. Further studies using tone bursts instead of clicks are recommended to help determine whether single-channel models are appropriate.

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1. Introduction

This thesis describes a fundamental study into a specific aspect of the behaviour of click-evoked otoacoustic emissions (CEOAEs). CEOAEs are acoustic signals emitted by the normal ear in response to click stimuli. In particular, the project examines what have been termed “nonlinear temporal interactions” in CEOAEs, which are the nonlinear interactions between multiple CEOAEs, evoked by clicks that are separated in time.

This chapter briefly summarises aspects of the anatomy and physiology of the mammalian cochlea, the phenomena of otoacoustic emissions and the issues of linearity and nonlinearity as relevant to this project. In addition, an important neural system – the olivocochlear efferent system – is introduced. Finally, the general aims of the study are listed: these are further expanded upon in the following chapter after a more detailed discussion of the issues that are the focus of this work.

1.1 The mammalian cochlea

The anatomy and physiology of the mammalian cochlea are reviewed in detail in Dallos *et al.* (1996) and briefly described here in the context of this thesis. The cochlea is a spiral, fluid-filled structure embedded within the temporal bone. It is wider at one end, the base, and progressively tapers along its spiral structure towards its apex. Sound vibrations from the external ear canal are transmitted by the middle-ear ossicles to a membrane at the base of the cochlea, the oval window. The mechanical impedance of

the ossicular chain can be controlled by a reflex mechanism involving the middle-ear muscles. This middle-ear reflex therefore provides a biological control on the transmission of sound through the middle-ear.

The bony cochlea is divided internally by the membranous labyrinth to form three canals or *scalae* – these are termed scala vestibuli, scala media, and scala tympani respectively. Scala media and scala tympani are separated by the basilar membrane (BM), which supports a collection of cells known as the organ of Corti. The organ of Corti contains supporting cells, as well as the sensory cells of the cochlea, the outer and inner hair cells (OHCs and IHCs). The width of the BM increases and its stiffness decreases longitudinally from the base to the apex of the cochlea. Also running longitudinally along the cochlea, roughly in parallel with the BM, is a gelatinous structure known as the tectorial membrane. Bundles of stereocilia (or “hairs”) project from the tops of the hair cells towards the tectorial membrane, with the stereocilia of the OHCs embedded in it. The hair cells are mechano-electrical transducers: deflections of the hair bundles modulate ionic currents into the cells from the surrounding fluids, thereby modulating the cells’ internal electrical potentials.

Vibrations entering the cochlea at the oval window create fluid disturbances which in turn set up a longitudinal “travelling wave” of displacement along the BM, from the base towards the apex. The travelling wave and the physical arrangement of the BM and the tectorial membrane result in a relative shear between these two membranes, which is detected by the mechano-electrical transduction process of both types of hair cells. The IHCs synapse directly with the primary afferent neurones of the auditory system, thus initiating neuronal firing in response to sound. The OHCs in contrast do

not play a material role in initiating a neural response, but are thought to amplify the displacements of the BM, thus enhancing the auditory system's sensitivity to sound. The mechanism by which the OHCs amplify BM displacements is not entirely known, but is thought to involve a "reverse" electro-mechanical transducer action. The amplification of BM displacements by the OHCs also relies on active (energy-consuming) and physiologically vulnerable processes within the cochlea. Most forms of sensorineural hearing loss are considered to involve primarily an impairment of these "active processes" and thus of the mechanical response of the BM itself; rather than an impairment of the transduction of this mechanical response to a neural signal, or transmission of the neural signal to the brain.

The mechanical response of the BM is also the primary basis for the frequency analysis of sound by the auditory system. The travelling waves generated by pure tones of different frequencies peak at different locations along the BM, due to its impedance gradient from base to apex. Different sites along the BM therefore respond best to different frequencies, with high frequencies generating maximum response at the base and lower frequencies at locations progressively towards the apex. Although this basic tonotopic mapping of frequency to position along the BM is determined by its inherent structural properties, the amplification of the vibration at a particular point (due to the active process) also greatly enhances the frequency selectivity of the response of the BM. The active process operating through the OHCs is therefore responsible both for the extraordinary sensitivity of the ear to sound and for its great frequency resolution.

1.2 Otoacoustic emissions

Otoacoustic emissions (OAEs) (Kemp, 1978) are low-level acoustic signals that are generated within the normal cochlea, pass through the middle ear, and are measurable in the ear canal by means of a probe microphone and suitable recording techniques. They are measurable in both human and animal ears, although significant differences exist between OAEs recorded in different species (Probst *et al.*, 1991).

The generation of OAEs is thought to rely upon the same physiologically vulnerable active processes involving the OHCs that are responsible for the great sensitivity to acoustic stimuli and frequency selectivity of the normal cochlea. OAEs therefore provide a valuable noninvasive means of assessing the integrity of aspects of cochlear function that are essential for normal hearing, and OAE measurement has gained wide acceptance in recent years as a useful clinical tool (Robinette and Glatcke, 1997). As most forms of sensorineural deafness involve an impairment of the cochlea's active process, OAEs have acquired particular importance as a screening tool for deafness in infants. The success of OAEs in more detailed diagnostic applications has been limited in part by an as yet incomplete understanding of their basic properties and generation mechanisms (e.g. Kemp, 1997). However, from a research perspective, their non-invasive nature also means that OAEs offer the unique possibility of directly studying the mechanics of the normal human cochlea.

There are two broad groups of OAEs – spontaneous OAEs (SOAEs) and evoked OAEs. Evoked OAEs include a class evoked by transient acoustic stimuli, transient-evoked OAEs (TEOAEs), as well as distortion product OAEs (DPOAEs) and stimulus

frequency OAEs (SFOAEs). Click-evoked OAEs (CEOAEs) are the most widely used type of TEOAEs, and form the basis of this project.

The general techniques for the measurement of CEOAEs have been described by several authors (e.g. Bray, 1989; Kemp *et al.*, 1990; Decker, 1997). In summary, a stream of acoustic clicks is delivered to the ear, typically by a miniature transducer housed within a probe inserted into the external ear canal. The probe also houses a miniature microphone, which records the acoustic response in the ear canal following the delivery of each click. The responses to several hundred clicks are typically averaged in time in order to extract the (low-level) cochlear response from the background noise. Standardised techniques have been developed in order to reject excessive levels of background noise and to discriminate between a “true” cochlear response and that due to the ear canal and middle ear alone.

In normal adults, a CEOAE typically presents as a decaying acoustic response that persists for approximately 20 ms following the click stimulus and contains a mixture of frequencies predominantly between 0.5 and 4 kHz. The waveform also exhibits a degree of frequency dispersion, with the higher frequency components dominating the earlier waveform time segments, and lower frequencies occurring later in the waveform.

SOAEs, which may be measured in the absence of any external stimulation, are narrowband signals typically detected by a spectral analysis of the sound field in the closed ear canal. However, these signals may also be repeatedly synchronised by streams of clicks such as those used to measure CEOAEs (e.g. Gobsch and Tietze, 1993; Wable and Collet, 1994; Smurzynski and Probst, 1996; Burr *et al.*, 1997). The averaged

click response may therefore contain “synchronised SOAEs” (SSOAEs) as well as a true CEOAE response. SSOAEs may be distinguished from conventional CEOAEs by their relative lack of frequency dispersion across the response waveform and their relative insensitivity to the level of the stimulus click.

CEOAEs can be recorded in essentially all normal adult ears (Probst *et al.*, 1991; Kapadia and Lutman, 1997). They are easily measured in co-operative subjects and their basic properties have been extensively studied (Probst *et al.*, 1991). These factors and the relatively wide-band nature of a click stimulus make CEOAEs a potentially powerful tool for the study of the cochlea.

1.2.1 Role of OAEs in basic research

Despite the major advances in recent years in the technology and techniques used in making direct experimental measurements of cochlear mechanics, such measurements remain seriously constrained by the need to make a physical opening into the cochlea. Although the potential effects of this procedure on the state of the cochlea can be monitored (e.g. by measuring neural thresholds before and after the opening is made), this does not assure that all aspects of the mechanical measurements made are the same as they would have been in the intact cochlea. For example, Cooper and Rhode (1996a) identified “fast travelling waves” as well as more conventional “slow travelling waves” in the responses to clicks in the chinchilla and guinea pig cochlea. The fast travelling wave resulted in a BM response at the apex within 100 μ s of the onset of motion of the middle-ear ossicles, far earlier than that due to the conventional travelling wave. However, in a careful discussion of their findings Cooper and Rhode (1996a) suggest

that the fast travelling wave might not be present in a truly intact (sealed) cochlea, and might in fact be an artifact of artificially opening the cochlea. They also point out that a number of other investigations of cochlear mechanics have been conducted under experimental conditions similar to theirs and have reported significant features that may correspond to the (possibly artifactual) fast travelling wave.

A further difficulty in direct measurements of cochlear mechanics is the physical inaccessibility of most of the mammalian cochlea, other than by the most radical and damaging surgery. As a result, the vast majority of experimental data come from the basal region (Rhode and Cooper, 1996), with some (relatively recent) data from the apical turn. Furthermore, significant differences (particularly in relation to tuning properties) between cochlear responses at the base and apex have been noted (Patuzzi and Robertson, 1988; Cooper and Rhode, 1995; Cooper and Rhode, 1996b).

Such considerations, coupled with the possibility of species differences, emphasise the value of experimental data from the human ear that may either corroborate or challenge the findings of direct measurements in laboratory animals. Although OAEs afford an indirect and incompletely understood window on the human cochlea, they represent perhaps the only available instrument to probe its mechanics, independent of the following neural stages of the auditory system. As a research tool, they may thus provide a useful complement to direct physiological measurements in other species and to psychoacoustic experimentation in human subjects.

1.3 The olivocochlear efferent system

In addition to the afferent or ascending neurones, which convey information from the peripheral auditory system towards the brain, the mammalian cochlea is supplied by an extensive efferent or descending system of neurones (Spangler and Warr, 1991; Guinan, 1996). These neurones originate in the superior olivary complex within the brain stem, which itself receives ascending and descending neurones from other parts of the auditory system. A subgroup of these efferent neurones (the medial olivocochlear neurones) synapse directly with the OHCs. The efferent olivocochlear system therefore provides for the possibility of neural control of the mechanics of the cochlea, mediated by the activity of the OHCs. Several physiological studies have supported this hypothesis, by monitoring cochlear responses to sound while simultaneously stimulating the olivocochlear system (reviewed in Guinan, 1996; Murugasu and Russell, 1996). A suppressive effect of the olivocochlear efferent system on OAEs has also been reported (reviewed in the next chapter), and may have relevance for the present project. Paradoxically, there is little evidence for a functional significance of the olivocochlear efferents (Scharf *et al.*, 1997), and their exact role in normal audition remains the subject of considerable investigation and debate.

1.4 Linearity and nonlinearity

Any physical or biological system that converts a quantitative input into a quantitative output may be described at its simplest level by its input-output (I-O) function, which

describes the instantaneous relationship between the magnitudes of the input and output.¹

For the purposes of this project, linearity of a system is defined as the observance of linear superposition between input and output. In other words, if an input x_1 results in an output y_1 , i.e.

$$x_1 \rightarrow y_1$$

(where the arrow represents the conversion of an input to an output)

and

$$x_2 \rightarrow y_2$$

then linear superposition implies that

$$(x_1 + x_2) \rightarrow (y_1 + y_2) \quad \dots \text{Eqn. 1.1}$$

i.e. the output of the system to the summed inputs is exactly the sum of the outputs to the individual inputs.

Any system that does not so demonstrate linear superposition may be regarded as a nonlinear system.

¹ Strictly speaking, an I-O function fully describes only a “static” system, i.e. one for which the outputs at any instant depend only on the inputs at the same instant (e.g. Sinha, 1991). For a complete description of a system whose outputs may depend on the past as well as the present inputs, a description of its phase and frequency response characteristics is also required. These are ignored for the purpose of the present discussion of linearity.

In the special case where $x_2 = Ax_1$, where A is a (scalar) constant,

$$(x_1 + x_2) = (1 + A)x_1$$

i.e. the summing of inputs represents a numeric scaling of a single input, for example for $A = 1$, $x_1 + x_2 = 2x_1$. Adherence to linear superposition in this case implies that the system output is simply scaled by an identical amount, and that the system's I-O function describes a straight line (on a linear co-ordinate system).

Conversely, a violation of Equation 1.1 implies that a numeric scaling of the input does not simply result in an equal scaling of the output. The I-O function in this case does not describe a straight line, and the system may be said to exhibit a “static” nonlinearity.

A compressive static nonlinearity implies that an increase of the system input by a given scaling factor results in a *less than* proportional increase of the output. Such a nonlinearity is typically exhibited by an otherwise linear system when it is driven into overload by a sufficiently large input. Any description of a system as being linear must therefore be viewed with reference to a specified or assumed input range, and the degree of nonlinearity of a system may also depend upon the magnitude of the input.

Despite some initial controversy, it is now clearly established that the mechanics of the cochlea exhibit a fundamental nonlinearity, which is attributable to a static compressive nonlinearity in the vibrations of the BM across most of the normal range of hearing (Ruggero, 1992; Patuzzi, 1996).

A particular type of nonlinear behaviour that has been widely studied in the cochlea is that of the “suppression” of the response due to one input by the presentation of an additional input. The property of linear superposition described in Equation 1.1 may equivalently be viewed as a system property whereby the output due to any single input is *unaffected* by the presentation of other inputs: the suppression described above can therefore be seen to be a violation of superposition, and an indication of system nonlinearity. The suppression (reduction in amplitude) of the response due to one input by the presentation of another represents a specific instance of a nonlinear interaction between the two inputs. Clearly, the measurement of such suppression in any system requires the use of inputs or techniques that permit the isolation of the system output due to each input individually.

The concepts of static nonlinearity and suppression as described here are both crucial to the present study: their application to CEOAEs will be described in the following chapter and they will be referred to frequently throughout the remainder of this thesis.

1.5 General aims

The main aim of this project was to provide a detailed parametric characterisation of the nonlinear interactions between the CEOAEs evoked by a pair of stimulus clicks separated in time. Such interactions have been previously reported in the literature, but not studied in great detail nor completely understood. Aspects of these interactions may shed light on fundamental issues of the generation and propagation of CEOAEs within the cochlea, and on aspects of nonlinear behaviour in the human cochlea.

In addition, the project aimed to investigate the *accumulation* of such nonlinear interactions when more than two stimulus clicks were used. This was motivated by untested hypotheses in the literature as to the nature of such accumulation. The issue is also important for an understanding of the properties of CEOAEs when measured using stimulus clicks at relatively high click rates.

These general aims and a number of specific issues that arise in considering them are described in greater detail in the following chapter.

2. Nonlinearity and suppression in TEOAEs

The project described is concerned with nonlinear behaviour in the normal human cochlea as evidenced by the suppression of a transient-evoked OAE by additional acoustic stimulation. More specifically, the phenomenon studied is that of the reduction in amplitude (suppression) of a CEOAE, under the influence of one or more additional clicks delivered to the same ear. Thus the suppressor, like the stimulus, is an acoustic transient and the stimulus and suppressive transients are nominally discrete, and possibly distinct (non-overlapping), events.

In attempting to examine the particular phenomenon described, it is also necessary to consider other potentially related suppressive phenomena reported in the literature. These other suppressive phenomena include suppression of a TEOAE by a *continuous* ipsilateral signal, as well as suppression due to contralateral stimulation. In addition, as described in Section 1.4, suppression of a response due to an additional stimulus is an indication of nonlinearity; and the basic (“static”) nonlinearity of CEOAEs is well-recognised and of direct relevance to this study.

The present chapter therefore reviews the literature pertaining to all of the above nonlinear and suppressive phenomena. The review is sectionalised, with greater emphasis placed on the sections most directly concerned with the phenomenon under investigation – i.e. suppression of CEOAEs by transient ipsilateral suppressors.

The chapter concludes by detailing the specific issues to be addressed in the project.

2.1 “Static” amplitude nonlinearity

The initial report of CEOAEs (Kemp, 1978) drew attention to one of the key features of the response: the compressive nonlinearity of its level function, which plots the amplitude (or level) of the response versus that of the stimulus click.² Thus it was noted that progressive increases in stimulus click level resulted in less than proportional increases in the level of the response. This (static) CEOAE level function nonlinearity was immediately linked by Kemp to the essential amplitude nonlinearity of cochlear mechanics (for which there was growing evidence; e.g. Rhode and Robles, 1974) and was taken as strong evidence of the physiological nature of the response measured.

The nonlinearity of the CEOAE level function was subsequently documented by a number of other studies (e.g. Wilson, 1980; Kemp and Chum, 1980; Kemp *et al.*, 1986; Probst *et al.*, 1986), and is indeed exploited in distinguishing between the “true” CEOAE response of cochlear origin, and the acoustic response of the ear canal and middle ear to the click. As this ear canal acoustic response (sometimes referred to as the “click artifact”) has a ringing component that can last for several milliseconds, it can impinge upon the temporal window of the CEOAE. However, the growth of the ear

² Note that the term “input-output (I-O) function” is often used in the literature to refer to a plot of the CEOAE amplitude (output) versus click amplitude (input), rather than the term “level function” as used here. However, as described in Chapter 1, in this thesis the term I-O function is reserved to describe the underlying *instantaneous* relationship between the input and output of a system. Nonetheless, the *nonlinearity* of the level function is directly derived from (and therefore equivalent to) that of the underlying I-O function.

canal response amplitude with click level is linear (Kemp *et al.*, 1986; Grandori and Ravazzani, 1993): the canal response may therefore be removed by means of a cancellation process usually referred to as the derived nonlinear (DNL) technique (Kemp *et al.*, 1986; Kemp *et al.*, 1990).

There are two commonly-used variations of the DNL technique. The approach most often used in routine CEOAE measurements may be termed an “on-line” method.

In the “on-line” DNL method (Kemp *et al.*, 1986; Kemp *et al.*, 1990), the click stimuli are divided into groups of four, consisting of three clicks of identical amplitude and polarity, followed by a single click of three times that amplitude and of inverted polarity. The responses to all four clicks (as recorded by the probe microphone) are time-averaged into a single buffer *on-line*, i.e. as the recording is made. The net result of this stimulation and averaging scheme is that linear components of the response (that are exactly three times as large in response to the larger click as in response to the smaller) exactly cancel each other. This cancellation leaves only a nonlinear residual, which is taken to be entirely of cochlear origin. Note that this technique also exploits another property of CEOAEs – that of a symmetry in polarity, whereby an inversion of click polarity produces an inverted response which is of otherwise identical waveform and amplitude (Kemp and Chum, 1980; Kemp *et al.*, 1986; Lina-Granade and Collet, 1995).

In the “off-line” variation of the DNL technique (e.g. Probst *et al.*, 1986; Prieve *et al.*, 1996; Kapadia and Lutman, 1997), CEOAEs in response to clicks of two different click levels are first recorded separately, each being the conventional average of responses to

clicks of fixed level. These responses are then mathematically scaled and subtracted in an off-line analysis that once again exactly cancels linearly-scaling components, leaving only a nonlinear residual of cochlear origin. The off-line cancellation technique does not necessarily rely on a symmetry in polarity of the CEOAE response. Both techniques do also rely on the lack of any significant phase or time shift between the responses to the two different click levels.

Both the on-line and the off-line variations of the technique would give an identical DNL response, assuming identical click levels (and linear test equipment) are used. However, in the on-line method, only the (derived) nonlinear response is obtained, without any measure of the primary (“linear”) responses. Further, although the DNL response in both approaches is governed by both the amplitude of the primary response and the degree of nonlinearity of the level function, the on-line method does not permit a separate quantification of these two factors.

The degree of nonlinearity of the basic CEOAE level function is most conveniently observed by plotting the function on a log-log scale, and is then represented as the slope in dB/dB. The extreme slope values possible (for a compressive nonlinearity) are 0 dB/dB, representing a fully-saturated level function, and 1 dB/dB, representing a completely linear level function. For CEOAEs recorded in adult ears, level function slopes of the order of 0.5 dB/dB are typically reported (e.g. Kemp and Chum, 1980; Kemp *et al.*, 1990; Grandori and Ravazzani, 1993).

A final important property with regard to CEOAE amplitude nonlinearity has been noted in the literature (Wilson, 1980; Grandori and Ravazzani, 1993): the degree of

compressive nonlinearity increases with increasing latency of the waveform time-segment (within the overall waveform duration of typically 20 ms). Thus the later waveform segments, which are typically of lower amplitude, also exhibit less amplitude growth with increases in stimulus click level. (As mentioned in Section 1.2, these later waveform segments also tend to contain the lower-frequency components of the response.)

2.2 Suppression by transient signals

2.2.1 Suppression by an additional click

Suppression of a CEOAE by an additional click was first described by Kemp and Chum (1980) as part of a broader investigation, the purpose of which was “to develop a quantitative and qualitative description of the physical properties of the generator of click stimulated acoustic emissions based solely upon acoustic observations in the meatus.” To that end, the authors first formulated an empirical mathematical relationship between the energy input, E_1 , and energy output, E_2 , of the CEOAE generator process, when activated by a single click; i.e.

$$E_2/E_1 = AE_1^C$$

This relationship incorporated a “scaling factor” A and a “compression factor” C , and embodied the compressive nonlinearity of the CEOAE level function described in Section 2.1. Both A and C are determined by the inherent properties of the emission

generator process, and the authors estimated values for these parameters from CEOAE level function data from a sample of 12 ears.

Based on the above relationship, Kemp and Chum next developed predictions of suppressive behaviour when the generator process was excited by a *pair* of clicks, i.e. the suppression by an additional click under discussion here. The authors thus predicted that the response specific to a test click T, when recorded in the presence of a large suppressor click S,³ would suffer a degree of suppression, which would depend on two parameters. These parameters were the intensity of click S relative to that of click T, and the compression factor *C* described above. (Suppression did not depend on the absolute intensity of the test click in their predictions, in keeping with their use of a single-valued compression factor, representing a constant degree of compression over the level function of interest.)

Kemp and Chum (1980) recognised, however, that a description of such suppression needed to take into consideration at least one further factor. This was the *time interval* between T and S – that is to say, there needed to be a temporal limit to the nonlinear interaction between the two clicks. However, the predictions of suppression that the authors had developed could not take into account the inter-click time interval, as these predictions were based upon single-stimulus level function behaviour.

³ Kemp and Chum (1980) actually denote these two clicks as “S” (stimulus) and “M” (masker) respectively. In order to reconcile the differences in nomenclature used by different authors, the nomenclature used in the present study is also adopted in discussing all the published literature in this and other chapters.

Kemp and Chum (1980) therefore further conducted a short series of click suppression measurements, which enabled them firstly, to examine their predictions of suppressive behaviour and secondly, to assess the temporal limits of the interaction between the clicks. They used a novel measurement paradigm (a modified version of which is described in detail in Chapter 3) that allowed them to cancel the suppressor click and its corresponding CEOAE from the response to the pair of clicks presented jointly. The result of this cancellation paradigm was thus the test-evoked CEOAE alone, but crucially, subject to any influence of the suppressor click.

Only three ears were tested in these experiments, and much of the data presented and discussion were based on tests in one ear only. Conventional audiometric data and related subject information were not reported.

A restricted set of click amplitudes was used, with most of the data being for a test click level of 30 dB SL and a suppressor click at either 40, 50 or 60 dB SL. Various sets of inter-click intervals were used for different measurements, within the range from the suppressor *leading* the test by 10 ms to *following* the test by 25 ms. Nevertheless, these data showed that: (a) the CEOAE response to the test click T was indeed partially suppressed by the presence of the suppressor click S; (b) the amount of suppression increased as the intensity of S relative to that of T was increased; and (c) that the time interval between the two clicks strongly influenced the degree of suppression, with greater suppression as this interval was reduced.

In examining the effect of the inter-click interval, the authors also concluded that the suppressor click S needed to be presented within about -6 and $+3$ ms of the test click T, in

order to influence the response to T. However, these temporal limits were based on one approach to analysing the results, whereas some of the data (in which unusually long-lasting CEOAEs were shown) indicated suppression occurring with click S presented as late as 25 ms following click T (Fig. 4, p. 221). The authors acknowledged that their data appeared somewhat to contradict some of their conclusions with regard to the emission generator process. They additionally raised new hypotheses to address the discrepancies, but these remained untested.

Finally, Kemp and Chum (1980) made approximate mathematical predictions of the time domain patterns of click suppression, by computing the suppression that would be generated by a compressive nonlinearity acting at the output of a narrow filter, the parameters of which were calculated based on previously published psychophysical data (Duifhuis, 1973). For a degree of nonlinearity compatible with the experimental data, the predicted suppression followed a qualitatively similar pattern to Kemp and Chum's measured suppression data. However, some differences were also observed, especially in relation to the dependence of the suppression upon the suppressor level.

Kemp and Chum (1980) concluded that their suppression data could be largely explained (at least qualitatively) on the basis of a static compressive nonlinearity. However, although they observed differences in the properties of the suppression due to leading as opposed to following suppressors, they did not draw any conclusions as to possible differences in the underlying mechanisms. Furthermore, the authors noted that the effect of a following suppressor did not commence until 7-10 ms after its own presentation, but most of their analyses were based on the CEOAE amplitude in the 5-20 ms waveform segment (effectively the whole CEOAE waveform). Measurements in more restricted

waveform segments would have allowed a more appropriate evaluation of the suppression due to following suppressors. Finally, although Kemp and Chum (1980) utilised a novel technique in order to obtain their seminal results, some of their data were subject to – and therefore their results restricted by – the technical limitations of their equipment, principally relating to imperfect cancellation of the suppressor click.

In recognising that their experimental data were limited, Kemp and Chum (1980) described their calculations as preliminary and suggested that the work described would prove useful in future studies. However, those investigations (into click suppression of CEOAEs) have not been followed up to any extent by other workers until relatively recently.

Part of the reason for the relative lack of subsequent investigation into this type of suppression of CEOAEs is the technical difficulty of making artifact-free measurements. A more fundamental reason may well have been a lack of an obvious practical benefit from this area of research. CEOAEs have traditionally been measured using stimulus click rates at which no suppression of this sort would be expected, at least in the majority of subjects. However, the advent of newer measurement techniques (Thornton, 1993b) has made possible the use of much higher click rates, at which some degree of suppression would be expected and has indeed been reported (Thornton, 1993b; Picton *et al.*, 1993). A further advance in the field has been the demonstration of suppression of CEOAEs by acoustic stimulation of the contralateral ear (Collet *et al.*, 1990) (described in more detail in Section 2.5 below). This contralateral suppression indicates an influence of the olivocochlear efferent system on CEOAE amplitudes, and as the efferent system includes an *ipsilateral* as well as a contralateral pathway, an efferent role in the CEOAE

suppression at high click rates has been suggested (Thornton, 1994; Lina-Granade *et al.*, 1997).

Prompted partially by the above developments, a few authors have relatively recently reported new data on suppression of a CEOAE by an additional click, presented at various times relative to the test click (Tavartkiladze *et al.*, 1994; Lina-Granade and Collet, 1995; Tavartkiladze *et al.*, 1996; Kevanishvili *et al.*, 1996).

Tavartkiladze *et al.* (1994) used a slightly different technique to that of Kemp and Chum (1980), in which they subtracted the response obtained for the suppressor click alone (in a separate measurement) from the composite response to the paired clicks. This “off-line” subtraction was again held to reveal only the test-evoked CEOAE, subject to the influence of the suppressor. However, the technique relies on an assumption that may be important, as described below.

Tavartkiladze *et al.* (1994) in some respects explored an even smaller range of test parameters than Kemp and Chum (1980). They only used suppressor clicks that *preceded* the test click (corresponding to negative inter-click time intervals) by 1 to 30 ms, a single test click level (20 dB SL) and a single suppressor click level (at 26 dB above the test click). Five ears were tested. Their findings were broadly consistent with those of Kemp and Chum (1980), although quantitative comparisons between the two sets of results are hampered by the different methods of calculating CEOAE amplitude used in the two studies.

However, there are two important differences in the results reported in these two studies. Firstly, Tavartkiladze *et al.* (1994) reported that the suppressor click could *enhance* as well as suppress the CEOAE elicited by the test click. This contrasts with the data of Kemp and Chum (1980), in which the suppressor click had either a suppressive effect or no effect on the CEOAE. Tavartkiladze *et al.* (1994) regarded the finding of CEOAE enhancement as surprising, and suggested that the phenomenon was worthy of further investigation.

Tavartkiladze *et al.* (1994) also reported that their leading suppressors caused “more effective reduction of long-latency emissions”. This result is not observed in the single set of data in which suppression was reported within restricted waveform segments by Kemp and Chum (1980) (Fig. 5(b), p. 222). The finding is potentially significant, given the established increase in the degree of CEOAE level function nonlinearity with latency (Section 2.1). However, the data presented by Tavartkiladze *et al.* (1994) in this regard (one pair of waveforms from each of two subjects) are not entirely convincing and they did not quantify suppression within restricted waveforms segments as would be necessary to demonstrate the effect clearly. The measurement of suppression within small waveform segments would also have been valuable in studying the enhancements observed by Tavartkiladze *et al.* (1994); as they observed that they reflected “the enhancement of the long-latency TEOAE components”. Other such (relatively localised) enhancements in their data may well have been missed if they were swamped by suppression in the other parts of the CEOAE waveform.

Tavartkiladze *et al.* (1994) obtained an atypical finding in one of their five subjects, who was reported as being the only one exhibiting an SOAE. In this subject, although the

CEOAE showed the typical reduction in suppression as inter-click interval was increased, a “second phase” of increased suppression was observed for inter-click intervals as large as 20 ms. The measurements of Kemp and Chum (1980) did not extend to such large inter-click intervals for leading suppressors.

In evaluating the qualitative differences in the results between Kemp and Chum (1980) and Tavartkiladze *et al.* (1994), it is important to recognise a limitation of the technique used by the latter authors. It relies on the assumption that the CEOAE elicited by the (leading) *suppressor* click is unaffected by the presence of the following *test* click. This would certainly *not* be true in general, as demonstrated by the data of Kemp and Chum (1980), who found that a CEOAE can indeed be suppressed by a following suppressor. However the assumption may be valid to a first approximation for the single condition of click intensities used by Tavartkiladze *et al.* (1994), i.e. test click at 20 dB SL and suppressor at 46 dB SL. Nevertheless, the technique devised by Kemp and Chum (1980) for their study does not make this assumption, and it is possible that the differences reported between the two studies may be due to a partial error in the assumption made by Tavartkiladze *et al.* (1994).

One of the aims of the study of Tavartkiladze *et al.* (1994) was to investigate the potential involvement of the olivocochlear efferent system in ipsilateral CEOAE suppression, in the light of the accepted efferent role in contralateral suppression. The authors concluded, because of the short latencies of the effects they measured, that “efferent effects observed were negligible in our experiments compared with the CEOAE suppression of exclusively cochlear origin.” However, they further stated that efferent contribution to CEOAE ipsilateral suppression requires thorough investigation.

In this regard, it should be noted that Kemp and Chum (1980) did not make any mention of the efferent system in discussing their suppression data. This is probably because: (a) the efferent effect on CEOAEs due to contralateral acoustic stimulation had not been reported at that time; and (b) Kemp and Chum (1980) began their investigations into suppression on the basis of the inherent nonlinear behaviour of CEOAE level functions, which was held to reflect properties intrinsic to the CEOAE generator process. Not surprisingly therefore, the discussions in Kemp and Chum (1980) made the implicit assumption that the CEOAE suppression reported reflected a direct cochlear, rather than an efferent-mediated, phenomenon.

Lina-Granade and Collet (1995) studied the suppression of the CEOAE evoked by a test click under the influence of an *equilevel* suppressor click only, using the same cancellation technique as Kemp and Chum (1980). They conducted three experiments with 12 subjects, with test and suppressor clicks levels both at either 65 or 69 dB SPL (approximately) as measured in the ear canal. Three different ranges of inter-click intervals were used – suppressor leading the test by 30 ms to 3 ms, leading by between 12 and 1 ms, and following the test by between 3 and 21 ms. As with Tavartkiladze *et al.* (1994), these authors did not quantify suppression within restricted time segments, using instead only a whole-waveform measure (the boundaries of which varied between the three experiments).

For leading suppressors, Lina-Granade and Collet (1995) observed suppression for inter-click intervals less than 9 ms, increasing as the interval shortened but levelling off between the intervals of 2 and 1 ms. For following suppressors, they observed small

and just-significant amounts of suppression at two isolated inter-click intervals (3 and 9 ms) only. These authors' data may be compared to a very limited subset of the original results of Kemp and Chum (1980), in which equilevel clicks were used. The comparison is necessarily also highly approximate, as the relevant data of Kemp and Chum are reported as "equi-response" curves, which require the (unspecified) CEOAE level functions in order to effect a comparison. Under the assumption of a typical level function slope of 0.5 dB/dB (see Section 2.1), the two sets of results are broadly similar.

Lina-Granade and Collet (1995) also conducted a fourth experiment in order to check for possible errors in their cancellation technique, which relied on the accurate inversion of the suppressor clicks and associated CEOAEs when the corresponding electrical clicks were inverted. They reported that no errors could be detected in this regard, which implies that these authors' data (albeit over a more limited range of clicks levels) were not subject to the artifacts and constraints due to the limitations of the test equipment that were suffered by Kemp and Chum (1980).

In common with Kemp and Chum (1980), and in contrast with Tavartkiladze *et al.* (1994), Lina-Granade and Collet (1995) did not report any enhancements of CEOAEs. As previously noted however, the use of whole-waveform segments only to quantify suppression may have made the measures insensitive to local enhancements of the type reported by Tavartkiladze *et al.* (1994).

Lina-Granade and Collet (1995) interpreted their overall results as being most indicative of some type of "adaptation of the response by the outer hair cells". However, they appear to argue against the involvement of interactions in the mechanical vibrations

along the basilar membrane and did not discuss the link between such interactions and hair cell “adaptation”. In this connection, the authors cited a report of sensitivity to stimulus polarity in hair cell adaptation (Howard and Hudspeth, 1987) and suggested that the alternated polarity of their suppressor clicks may have augmented the observed suppression. They did not, however, test the polarity-sensitivity of the phenomenon. (Their fourth experiment referred to above confirmed the polarity insensitivity of their equipment and of the conventional CEOAEs measured, rather than of the suppression phenomenon.)

Unlike Kemp and Chum (1980), Lina-Granade and Collet (1995) made no direct connection between click suppression and a static compressive nonlinearity. They also made no mention of a possible olivocochlear efferent involvement in the phenomenon. In concluding, they acknowledged the tentative nature of their interpretations and stated that further studies were needed.

Following on from their earlier report described above, Tavartkiladze *et al.* (1996) reported on CEOAE suppression effected by bursts of noise. This report was based on “an extremely long-lasting experiment” in one subject only and also included a further set of measurements on suppression by a leading click. Click levels here were as in their previous report, i.e. test click at 20 dB SL and suppressor at 46 dB SL, with the suppressor leading the test click by between 1 and 30 ms. The authors observed suppression for inter-click intervals of about 4 ms or less, again utilising the whole waveform to quantify CEOAE amplitudes. In this case, however, no instances of CEOAE enhancement were reported. As the main focus of their study was CEOAE suppression by noise bursts, the authors did not discuss their click suppression results in

detail. They did however reiterate that the main effects could be attributed exclusively to intracochlear processes, because of their short latency.

Kevanishvili *et al.* (1996) used the same technique as Tavartkiladze *et al.* (1994) to examine again the effects of leading suppressor clicks only. However, these authors were the first since Kemp and Chum (1980) to conduct measurements over a *range* of relative levels of the two clicks.

Kevanishvili *et al.* (1996) measured suppression in six different conditions, in five subjects. Two experiments were conducted, both with a test click level of 15 dB SL. In the first, suppressor levels of 5, 15 and 25 dB SL were used, with a fixed inter-click interval of 5 ms. In the second, the suppressor level was fixed at 25 dB SL and inter-click intervals of 2.5, 7.5 and 10 ms were used. Kevanishvili *et al.* (1996) measured CEOAE amplitude using an unconventional measure based on the peak-to-peak amplitudes of dominant waves in the 8-17 ms segments of the waveforms. In accordance with Kemp and Chum (1980), they found suppression increased with increasing level of the suppressor relative to the test click and with decreasing inter-click interval. These authors' measurements also extended the range of measurements made by Kemp and Chum (1980) by including a condition of suppressor level *less than* test level (at a single value of inter-click interval). No statistically significant suppression was measured in this condition.

Although they used the same technique as Tavartkiladze *et al.* (1994), Kevanishvili *et al.* (1996) did not report any CEOAE enhancements. Furthermore, their data are even more subject to the violations of the assumption inherent in this technique, i.e. that the

CEOAE elicited by a leading suppressor click is unaffected by the presence of the following test one. This is because the suppressor click level did not exceed that of the test by as substantial a margin here as in Tavartkiladze *et al.* (1994). Indeed, the suppressor level was less than or equal to that of the test in two of the six conditions.

Kevanishvili *et al.* (1996) recognised that their results were broadly in agreement with those of Kemp and Chum (1980), but regarded their findings as theoretically unexpected. They made no concrete attempt at an explanation of the mechanism behind the effects, but speculated on the existence of “an essentially extra-receptor (para-auditory) contribution” to the CEOAE, implying presumably an influence of the central nervous system.

All of the above studies were aimed at characterising the effects on a conventionally recorded CEOAE of an additional (suppressor) click. In contrast, a recent body of work (Keefe, 1998; Keefe and Ling, 1998) utilised a closely related technique to introduce “a new class of otoacoustic emission measurements”. The technique was similar to that of Tavartkiladze *et al.* (1994), in that the composite response to a pair of clicks was obtained, and the separately obtained response to one of them (regarded by Tavartkiladze *et al.* (1994) as the “suppressor”) was subtracted off-line. However Keefe then also subtracted the response waveform separately obtained for the *other* (“test”) click. The result is a wholly nonlinear residual that would be zero in a completely linear system. It is akin to the derived nonlinear (DNL) response in conventional CEOAE measurements, described in Section 2.1 (and reduces to a version of it in the special case of an inter-click interval equal to zero.)

The work described by Keefe (1998) and Keefe and Ling (1998) is largely theoretical in nature, and scant data (comprising a small number of waveforms) were reported. In any case, although these results would be governed by the same suppression mechanisms as apply in the studies described above, the technique used did not permit the measurement of such suppression. This is analogous to the situation with the DNL technique in conventional CEOAE measurements – as described in Section 2.1, the DNL result is governed by the nonlinearity of the level function, but does not permit its characterisation. The main focus of Keefe's relevant discussions, rather, was in the improved cancellation of the stimulus click that his technique achieved, as compared to the conventional DNL technique. Thus, to the extent that a suppression mechanism is discussed, it is largely in the context of the static compressive nonlinearity of the CEOAE, rather than any other possible nonlinearities.

In conclusion of this section, a number of authors have studied the suppressive effects of an additional click on a CEOAE since the original, preliminary report of the phenomenon by Kemp and Chum (1980). Surprisingly, all of them have conducted measurements over even more restricted ranges of parameters than Kemp and Chum (1980). Nevertheless (with some minor exceptions), all of the subsequent reports have been broadly consistent with one or both of the general findings of Kemp and Chum (1980); i.e. that the suppression increases with reducing inter-click interval, and with increasing level of suppressor click relative to test click.

However, none of the above studies, including that of Kemp and Chum (1980), have conducted measurements over an adequately wide range of parameters in order to obtain a broad characterisation of the effects. Most have used relatively few subjects, and

provided little audiological or other related data. Somewhat differing results have been obtained, which may in some cases be due to differences in the measurement techniques used. A range of possible explanations for the phenomenon have been hypothesised, though none has been adequately tested.

2.2.2 Suppression by a noise burst

A small number of authors have studied the effects of an ipsilateral noise burst (rather than a click) on the CEOAE evoked by a closely-following click.

In a study motivated primarily by a desire to investigate psychoacoustic forward masking, Gobsch *et al.* (1992) measured both the subjective masking of the click and the suppression of the CEOAE by the noise burst in the same subjects. They used white noise of variable duration between 6 and 100 ms, followed by a variable delay of 5 to 40 ms and a single stimulus click. The masking and suppression experiments were done using clicks at 10 and 20 dB above the subjective click thresholds for each ear. The levels of noise required (a) to mask the subjective detection of the click; and (b) to “completely suppress” the CEOAE elicited by the click were separately determined. The authors reported that *suppression* of the CEOAE required masker levels approximately 35 dB greater than those required for subjective *masking* of the click, and also that this margin was relatively constant across the ranges of the two time parameters above. Gobsch *et al.* (1992) suggest that the masking phenomenon observed involved two processes – a central neural process which was active at low masker levels (at which CEOAE suppression was not observed), and a peripheral “receptor” process, active only at higher masker levels (at which CEOAE suppression was observed).

It is difficult to make quantitative comparisons between the suppression data of Gobsch *et al.* (1992) and the click suppression data discussed in the previous section, as the amount of suppression was not accurately quantified in this study. (The presence of suppression was in fact evaluated by a “blind” assessment of the waveforms by three experienced investigators). However, the data presented (Table I, p. 146) indicate that 45% of CEOAE records were judged to show at least some suppression under the influence of the preceding masker with a masker-click interval of 20 ms (measured from the *end* of the masker noise burst). Furthermore, 20% were judged to show CEOAE suppression with a masker-click interval as large as 40 ms. Although Gobsch *et al.* (1992) assume a direct, (wholly intracochlear) mechanism for the suppression they observed, the large masker-click intervals appear at odds with the minimum inter-click intervals required for click suppression reported by the authors discussed in the previous section.

In striking contrast with Gobsch *et al.* (1992), Berlin and co-workers conducted a similar series of experiments (Berlin *et al.*, 1994b; Berlin *et al.*, 1995b; Berlin *et al.*, 1995a; Hood *et al.*, 1995) in which they assumed that the suppressive effects measured were entirely due to the olivocochlear efferent system. Of these reports, Berlin *et al.* (1995b) is the only full-length publication, and will mainly be discussed here. In this study, a train of four clicks of level 65 dB peak SPL was presented at various intervals following a 65 dB SPL noise burst of duration 408 ms. The noise burst was presented in three ways – ipsilaterally, contralaterally and bilaterally. The effect of the noise burst on the CEOAE time-averaged for *all four clicks* was measured while varying the interval between the noise and the first click in the train from 1 to 200 ms. Limited data are presented for the ipsilateral noise condition, however maximum “forward suppression”

of the CEOAE (of the order of 1 dB) is reported for a noise-click interval of 1 ms, significantly less for an interval of 10 ms, and a negligible amount by an interval of 50 ms.

These authors assumed that the ipsilateral suppression observed was an olivocochlear efferent effect and indeed, equate the mechanisms for ipsilateral and contralateral suppression. However, it seems quite likely that significant direct interaction could occur between the cochlear responses to the noise burst and the following click, for the noise-click interval of 1 ms (and perhaps for somewhat greater intervals) as assumed by Gobsch *et al.* (1992). (Note that the 1 ms interval specified by Berlin *et al.* (1995b) between the end of the noise burst and the click onset refers to the electrical signals applied to their transducer, and the windowing function applied to the burst is not stated.)

Further caution must be applied in interpreting the results of these authors, because of the apparently serious flaw in their design in which the CEOAE response to *all four* clicks was averaged in measuring the suppression nominally for the noise-click interval for the *first* click in the train. (For example, for a nominal noise-click interval of 1 ms, responses to clicks at 1, 21, 41 and 61 ms following the burst were all averaged together.)

Berlin *et al.* (1995a) address this potential difficulty in a follow-up study (published as a conference abstract only) in which data were obtained for both a four-click train (as above) and for a design utilising a single click after each noise burst. Data were collected for bilateral noise presentation only, with a noise-click interval of 1 ms only. The authors report that the amount of suppression “appeared to be about the same” in the one-click and the four-click designs. Although they appear to consider this result as a validation of the four-click design, it may be regarded as somewhat surprising. This is because if there is

indeed a significant relationship between the noise-click interval and the amount of suppression (as reported in the earlier study, Berlin *et al.* (1995b)) then the four-click design would be expected to yield much *less* suppression than the single-click one. Once again, this study may be confounded by the likelihood of direct interactions between the cochlear responses to the noise burst and to the ipsilateral click that is presented 1 ms later.

Tavartkiladze *et al.* (1996) sought to separate the ipsilateral suppression effects due to the olivocochlear efferents and direct cochlear interactions. They measured the suppressive effects of a 10 ms noise burst presented ipsilaterally, commencing 15, 30, 45, 60 or 75 ms prior to the OAE-evoking click. They also conducted identical measurements for the noise burst presented contralaterally. Only one ear was tested, due to the long duration of the experiment.

For the ipsilateral presentation, the amount of suppression measured was just over 1 dB for a masker-click interval of 15 ms. Suppression for all other intervals was substantially less, at approximately 0.3 dB. When the noise burst was presented contralaterally, little effect of masker-click interval over the range tested was observed, and the amount of suppression was approximately the same as for ipsilateral presentation at the longer intervals, i.e. 0.3 dB. Noting that for a masker-click interval of 15 ms the click followed the masker *offset* by only 5 ms, Tavartkiladze *et al.* (1996) suggested that the greater amount of suppression in the ipsilateral case for this interval reflected an exclusively *intracochlear* suppression process. In contrast, for ipsilateral presentations with masker-click intervals of 30 ms or greater (for which a comparable magnitude and pattern of contralateral suppression was obtained) an ipsilateral *efferent* mechanism was suggested. Note that these conclusions cast further doubt on the

interpretation of their own data by Berlin *et al.* (1995b) discussed above, in which an efferent (rather than intracochlear) mechanism was assumed for intervals as short as 1 ms between the end of the ipsilateral noise bursts and the following clicks.

In summary of this section, although there may be some underlying links between the ipsilateral “noise suppression” discussed here and the click suppression discussed in the previous section (which is the main focus of the present study), previous authors have differing points of view on this issue. Data reported are relatively scant, and there remain some difficulties in interpreting the findings reported to date. Further research is required to address these and to clarify the mechanisms involved in this type of suppression.

2.3 Suppression due to high click rates

The literature discussed in Section 2.2 above pertains to two different aspects of suppression of CEOAEs by transient signals. These are (a) suppression of the CEOAE by an additional click and (b) suppression by a burst of noise. Although the scientific motivation behind the studies and the interpretations of the effects observed varied considerably, almost all the above studies involved experiments that were specifically intended to produce suppression of the CEOAE. In contrast, some of the information on CEOAE suppression comes from a body of work in which the suppression was not desired, but was an unavoidable by-product of the experimental technique. This applies to the literature describing CEOAEs measured at unusually high click rates, which has been briefly referred to previously. Although the CEOAE suppression observed at such high click rates may be regarded as suppression due to transient signals (i.e. the individual clicks within the click stream), it is described here as a separate section.

CEOAEs are traditionally measured at stimulus click rates that are low enough to allow the emission elicited by each click to decay before the subsequent click is presented. This limits the maximum click rate to about 50 click/s, at which rate a typical set of CEOAE measurements may take a minute or more to conduct. The main difficulty in using substantially higher click rates is in separating the multiple overlapping click stimuli and CEOAE responses. However, these difficulties can be overcome by the use of a technique, the application of which to CEOAEs was first described by Thornton (1993b) and shortly thereafter by Picton *et al.* (1993). This technique uses stimulus clicks presented in a particular type of mathematical sequence known as a maximum length sequence (MLS).

Clicks within a typical MLS are distributed at pseudo-random intervals, the click rate is therefore described in the present discussion in terms of *average* click rate within a sequence. (This is approximately half the *maximum* click rate, which is the reciprocal of the minimum inter-click interval.) From the composite response of the system to an MLS the (average) response to a single click may be obtained by means of a reconstruction algorithm. This reconstruction algorithm is essentially an “inverse superposition” operation – in a linear system therefore, the reconstructed response is identical to that obtained by the conventional measurement of the response to a single click (e.g. Eysholdt and Schreiner, 1982). Using this technique, CEOAEs have been recorded using average click rates up to 2500 click/s (Thornton, 1994). Further technical details concerning the use of the MLS technique in such and similar applications are given by Eysholdt and Schreiner (1982), Shi and Hecox (1991) and Thornton *et al.* (1994a).

The initial findings of Thornton and co-workers were described in Thornton (1993b) and Thornton (1993a). In these two studies, CEOAEs were recorded with the MLS technique and average click rates up to 420 click/s as well as with a conventional technique at a click rate of 33 click/s, using the same equipment for both types of measurements. Thornton (1993b) reported a progressive reduction in emission amplitude as the click rate was increased. This “rate suppression” effect was only quantified for the “nonlinear” component of the CEOAE waveforms, derived from response waveforms for clicks at levels of 65 and 75 dB peak-equivalent (pe) SPL (see Section 2.1). For the highest click rate of 420 click/s the amplitude of the nonlinear response (for the 5 to 12 ms waveform segment) was approximately 3 dB lower than that at the conventional rate of 33 click/s. These initial reports by Thornton focused primarily on the benefits of the MLS technique, in terms of speed of testing and signal to noise ratio, over the conventional technique of recording CEOAEs. Consequently, the mechanism underlying the rate suppression effect was not discussed in any detail.

Subsequent reports by Thornton and co-workers (Thornton, 1994; Thornton *et al.*, 1994a; Thornton *et al.*, 1994b; Thornton and Slaven, 1995) provided more detailed measurements and discussions of MLS suppression at high click rates. These results showed a continuing decrease in the amplitude (now of the linear component) of the CEOAE as the average click rate was increased to approximately 1900 click/s (Thornton *et al.*, 1994b) and 2500 click/s (Thornton, 1994; Thornton *et al.*, 1994a). However, it was noted (Thornton, 1994) that the majority of the total suppressive effect (of about 4 dB for the whole CEOAE waveform) had occurred by an average click rate of 1000 click/s and that very little further decrease in response amplitude occurred between rates of 1000 and 2500 click/s. Thornton *et al.* (1994a) and Thornton and Slaven (1995) also compared

the amount of suppression within successive waveform segments and found that the later segments showed proportionately greater suppression than the earlier ones.

There was an additional interesting feature of the rate suppression data reported by Thornton and co-workers (Thornton *et al.*, 1994b; Thornton, 1994; Thornton and Slaven, 1995). This was that as click stimulus rates were increased just above the conventional rate of 40 click/s, CEOAE amplitudes initially *increased*, before the more pronounced, progressive decrease in amplitudes. This apparent increase may well have been an artifact of the equipment or technique (bearing in mind that the response at 40 click/s was measured conventionally, and that at the higher rate using the MLS technique). However, it is particularly noteworthy in the light of the finding of Tavartkiladze *et al.* (1994) mentioned in Section 2.2.1 on click suppression, that a suppressor click can *enhance* as well as suppress the CEOAE elicited by another click.

In addressing the mechanism underlying the rate suppression measured, Thornton (1994) argued against “intrinsic adaptation of the hair cells” and suggested instead an ipsilaterally-activated olivocochlear efferent effect, similar to that involved in the contralateral suppression of CEOAEs previously reported by Collet *et al.* (1990). This explanation was supported by data that showed that the change in a given CEOAE waveform when suppression was induced by contralateral acoustic stimulation was similar in pattern to the change induced by increasing the stimulus click rate. Furthermore, when Thornton (1994) measured the amount of contralateral suppression at different (ipsilateral) MLS click rates, a decreasing amount of contralateral suppression was found as MLS rate increased. Thornton interpreted this finding as an indication of a

common mechanism underlying the two suppressive effects, with less suppression available to one as more was effected by the other.

Finally, Thornton (1994) presented rate suppression data from both ears of a patient with a unilateral acoustic neuroma. Such patients exhibit reduced or absent contralateral suppression, which is an indication of a disruption of the olivocochlear efferent innervation by the tumour (Maurer *et al.*, 1992; Prasher *et al.*, 1994; Maurer *et al.*, 1995). Thornton reported that while a large percentage decrease in the CEOAE amplitude (as click rate was increased) was found in the normal ear, very little was observed in the ear on the tumour side. A similarly small amount of rate suppression was reported as being observed in five other patients with recordable CEOAEs in the tumour ear. As the tumours in these cases would likely have affected the efferent supply to the cochlea, the relative lack of a rate suppression effect here strongly implicated an efferent role in the effect seen in normal ears.

Picton *et al.* (1993) published findings broadly similar to those of Thornton (1993b), in also describing the application of the MLS technique to measuring CEOAEs. These authors used click rates of up to 1000 click/s, at which they obtained a rate suppression equivalent to approximately 6 dB (relative to recordings at the conventional rate of 50 click/s).

However, the interpretation of the rate suppression effect by Picton *et al.* (1993) differed from that of Thornton and co-workers, in that these authors suggested a direct cochlear mechanism was responsible, rather than an ipsilateral efferent mechanism. The authors refer to the two-click suppression data of Kemp and Chum (1980) discussed in the

previous section, noting the similar effect reported there of increasing suppression with decreasing inter-click interval, and attempted to compare those results quantitatively to their own findings. As the MLS technique inherently involves clicks of equal level, only a very limited portion of the data of Kemp and Chum (1980) (presented in their “equi-response curves”, p. 225), were suitable for (indirect) comparison. From these printed curves, for the suppressor leading the test click by 2 ms and both clicks at 30 dB SL, Picton *et al.* (1993) estimated an effective loss of input gain equivalent to 5 dB. Then, assuming a level function slope of 0.3 dB/dB they calculated a suppression effect of approximately 1.5 dB. This was considerably less than the suppression obtained in their own MLS data of 4.5 dB, for an equivalent click rate of 500 click/s.

In fact, for the click levels and waveform segment in the data of Kemp and Chum (1980), a level function slope of 0.5 dB/dB would be more typical and the loss of input gain for an inter-click interval of -2 ms is closer to 6 than to 5 dB. The effective suppression as calculated by Picton *et al.* (1993) should therefore have been 3 dB, rather than 1.5 dB.⁴ Nonetheless, this remains less than the MLS rate suppression for equivalent click spacing. (The difference is also likely to have been somewhat larger had Picton *et al.* used the same waveform segment as Kemp and Chum (1980), i.e. 5-20 ms, to quantify the whole waveform, rather than the 2.5-20 ms segment as they did.) Picton *et al.* (1993) account for the difference in suppression by postulating that the continuous presentation of the click stimuli (as in the MLS technique) would result in an *additive* suppressive effect of two-click suppression. They therefore suggested that similar

⁴ Note that this calculation, which is necessary to compare the data of Kemp and Chum (1980) to those of Picton *et al.* (1993), also relies on the assumption that the CEOAE level function slope is *unchanged* by the introduction of the leading suppressor.

processes underlay the rate suppression they observed and the effects of a single click on the response to a following click.

Picton *et al.* (1993) further suggested that rate suppression (and by inference the click suppression observed by Kemp and Chum (1980)) may have been related to the same nonlinear system that determined the CEOAE level function. They did not however attempt to test this possibility.

Picton *et al.* (1993) also reported some *increases* in CEOAE amplitudes at increased click rates, revealed by certain stimulus conditions and analyses. However, the effects were not similar in nature to the amplitude increases reported by Thornton and co-workers (Thornton *et al.*, 1994b; Thornton, 1994), and Picton *et al.* (1993) in fact suggested that most, if not all, of the apparent increases in the case of their own data were artifactual.

The findings of Picton *et al.* (1993) also extended those of Thornton and co-workers in an important respect. In addition to using unipolar MLS click sequences (represented by the binary conditions of “click” and “no click”), Picton *et al.* (1993) also utilised *bipolar* MLS click sequences (represented by the binary conditions of positive and negative clicks). Bipolar sequences differ from unipolar ones in that the click rates are constant (it is the click polarities that are pseudorandomly distributed). The interpretation of the nonlinear effects observed (and in particular, relating them to the two-click observations) may therefore be simpler.

Picton *et al.* (1993) found that the magnitudes of suppression for bipolar and unipolar MLS stimulation were very similar, if the (constant) bipolar click rate was equated to the

average unipolar click rate. This finding was broadly consistent with the well-known polarity-symmetry of conventionally recorded CEOAEs (see Section 2.1), whereby exact inversion of click polarity results in an exact inversion of the response. However, Picton *et al.* (1993) did report slight changes in response morphology when using the bipolar technique at rapid rates. They therefore suggested that the polarity-symmetry property of CEOAEs may not hold in the special circumstances of the rapid stimulation rates used in their study. It should be noted, however, that these authors also encountered more troublesome residual stimulus artifacts for bipolar than for unipolar click sequences. They attributed these to (unspecified) polarity-related nonlinearities in their experimental equipment. It would therefore seem possible that the changes in response morphology above were related to *equipment* asymmetries or nonlinearities (possibly influencing the CEOAE responses), rather than a polarity asymmetry intrinsic to the CEOAEs themselves. The issue of the polarity-symmetry or otherwise of CEOAEs at high click rates therefore remains unresolved in the data of Picton *et al.* (1993).

Following the initial proposition by Thornton and co-workers of an ipsilateral olivocochlear efferent mechanism underlying the rate suppression effect, Norman *et al.* (1996) conducted a more detailed study on patients with acoustic neuromas but recordable CEOAEs. Consistent with their earlier findings (Thornton, 1994), a reduced amount of rate suppression was found in several of the neuroma ears. However, these data appeared to indicate that several other patients exhibited normal amounts of rate suppression, when their low initial CEOAE amplitudes were allowed for. Indeed, one patient exhibited a substantial amount of suppression despite a large neuroma, which the authors assumed would have completely blocked the efferent pathway. This finding led the authors to

conclude that an efferent effect may not have been the only mechanism involved in the rate suppression measured in these patients.

In a subsequent and more conclusive study into the role of the efferents in MLS rate suppression, Hine *et al.* (1997) recorded CEOAEs from the affected ears of five patients who had undergone a vestibular nerve section. As it is likely that this surgical procedure also severs the efferent supply to the cochlea, such patients provide a further means of assessing efferent effects in humans (Williams *et al.*, 1993; Giraud *et al.*, 1995; Scharf *et al.*, 1997). Hine *et al.* (1997) compared the CEOAEs recorded using the MLS technique at an average click rate of 2500 click/s to those recorded using a conventional technique at a rate of 40 click/s. Although the baseline CEOAE amplitudes (at 40 click/s) were lower than those for normally-hearing individuals (presumably as the majority of these patients suffered some degree of hearing loss), Hine *et al.* (1997) found that the rate suppression at the click rate of 2500 click/s was *proportionately* of the same magnitude as for normal subjects. In addition, these authors found that the absolute amount of the amplitude change between low and high click rates in these patients was similar to that for another group of subjects with similar ages and hearing threshold levels, but who had not undergone a vestibular nerve section.

Hine *et al.* (1997) therefore concluded that the MLS rate suppression was not due to an ipsilateral efferent effect, and suggested that wholly intracochlear processes were probably involved. They noted the earlier suggestion by Picton *et al.* (1993) of a possible link with the nonlinear processes underlying the CEOAE level function and stated that further research is required to explain the mechanisms involved.

In a separate study, Hine and Thornton (1997) examined the effect of the level of the stimulus clicks on MLS rate suppression. For click levels ranging from 43 to 68 dB pe SPL, they found no difference in the amount of suppression (as a proportion of CEOAE amplitude at a conventional click rate of 40 click/s) as click rate was increased. Slightly less suppression was observed the lowest click level of 38 dB pe SPL – however, it is likely that this effect was due to a greater influence of the noise floor on these measurements.

In the first detailed, independent study of CEOAEs measured using the MLS technique by authors other than Thornton and co-workers and Picton *et al.* (1993), Lina-Granade *et al.* (1997) conducted a set of experiments in which they examined the effects of stimulus click rate and level as well as of concomitant contralateral stimulation. These authors compared CEOAEs measured conventionally at a click rate of 50 click/s with those measured with the MLS technique at average click rates between 70 and 550 click/s. They found CEOAE amplitudes decreased significantly up to an average click rate of 165 click/s, but further decreases with click rate were not significant. In contrast with the findings of Hine and Thornton (1997), these authors also reported that the rate suppression effect was stronger at moderate click levels than at high ones. Thus, at their minimum click level of 63 dB SPL, the rate suppression corresponded to about 5 dB (for the whole waveform segment) while at the maximum click level of 75 dB SPL, it was somewhat less at 4 dB. This difference in suppression could be interpreted as a steepening of the CEOAE level functions as click rate was increased.

In keeping with the findings of Thornton (1994), Lina-Granade *et al.* (1997) also observed less suppression induced by broad-band noise presented contralaterally at high

ipsilateral click rates than at low ones. These authors also found a correlation across subjects between the amount of suppression due to increasing the click rate alone and due to contralateral stimulation alone.

Finally, in quantifying the CEOAE amplitude changes within waveform segments, Lina-Granade *et al.* (1997) observed greater amount of suppression for the later segments, both for rate suppression (as had earlier been reported by Thornton *et al.*, 1994a and Thornton and Slaven, 1995) and, in the same subjects, for contralateral suppression at the 50 click/s rate.

In their discussion of the possible mechanism of rate suppression, Lina-Granade *et al.* (1997) discussed the possibility of some sort of adaptation of the CEOAE generators, in particular of the outer hair cells. However, they noted that corresponding adaptation has not been observed in physiological investigations in mammals. The authors saw a stronger argument for an ipsilateral olivocochlear efferent involvement, as earlier proposed by Thornton (1994). They argued that this was supported by their findings of less contralateral suppression at high ipsilateral click rates, the increase in the CEOAE level function slope at high click rates (as had also been previously reported for contralateral stimulation), greater rate suppression in subjects with greater contralateral suppression, and the fact that both types of suppression showed stronger effects in the later waveform segments. As a final argument, they noted that an earlier published study (Veuillet *et al.*, 1991) that had examined CEOAE suppression due to a *contralateral* click stream had found increasing suppression with increasing (contralateral) click rates, in a manner that paralleled the rate suppression seen here.

One other group (Johannesen *et al.*, 1998) has recently published an independent report of CEOAEs measured using the MLS technique. They reported rate suppression broadly similar to that found by the previous authors, with a magnitude of suppression of approximately 10 dB as click rate was increased from a conventional rate of 30 click/s to an average MLS rate of 2000 click/s. However, these authors utilised a novel “semi-nonlinear” CEOAE scaling technique, which was designed to cancel stimulus artifacts without excessively reducing CEOAE amplitude. While it is difficult to gauge the effect of this scaling technique on their results, quantitative comparisons with the work of other authors should be made with caution.

Johannesen *et al.* (1998) sought primarily to describe the system and techniques they had developed, and their application to neonatal hearing screening. Although they note the rate suppression effect, they do not discuss its underlying mechanism.

Thus, considering the collective findings of the various authors discussed in this section, the weight of evidence (particularly taking into account studies involving patients) appears to favour a direct, cochlear mechanism for MLS rate suppression. There have, however, been some arguments in favour of an ipsilateral efferent mechanism. Assuming an entirely intracochlear mechanism, an additive accumulation of click suppression has been postulated to account for rate suppression, but no evidence for such accumulation of suppression has been obtained.

2.4 Suppression by continuous signals

The amplitude of a transient-evoked OAE may also be reduced by the concurrent presentation to the same ear of a *continuous* signal. Such suppression is relevant to the present study to the extent that the mechanisms of CEOAE suppression, whether by transient or continuous signals, may well be related. Studies into such suppression further provide information on some fundamental properties of CEOAEs, which are important for the interpretation of the main phenomenon under study here.

2.4.1 High-frequency suppressors

Both Kemp and Chum (1980) and Tavartkiladze *et al.* (1994), whose findings on click suppression were discussed in Section 2.2.1, also reported data on suppression of a TEOAE by an ipsilateral continuous tone. (Both sets of authors used a similar cancellation technique, in this case to eliminate substantially the pure tone signal from the microphone output, leaving the TEOAE waveform.)

Kemp and Chum (1980) measured CEOAEs in the presence of a pure tone of frequency between 750 and 1750 Hz and at various levels. These experiments were conducted in one ear only. The significant finding of these experiments was that suppression of this nature was highly frequency-specific. A pure tone of a particular frequency only suppressed those components in the CEOAE that were themselves at the same or at adjacent frequencies. Increasing the intensity of the suppressor tone increased the magnitude of the suppression and also suppressed a wider frequency band within the CEOAE. Thus, Kemp and Chum (1980) concluded that nonlinear interactions occurred

only between *similar frequency components* and interpreted their results as being indicative of a CEOAE generator process that is distributed over many narrow-band, nonlinear channels. The net (broadband) CEOAE is then a (largely linear) summation of the outputs from these notional generator channels, with little influence of one generator on the output from another.

Tavartkiladze *et al.* (1994) also measured the influence of ipsilateral pure tones on CEOAEs. The pure tones used appear to have been varied across various frequency segments, within the overall range of 500 to 5000 Hz. Three ears were tested in these experiments, using a technique much the same as that of Kemp and Chum (1980). However, Tavartkiladze *et al.* (1994) also extended their measurements to TEOAEs evoked by tone bursts. Furthermore, Tavartkiladze *et al.* (1994) presented their findings in the form of iso-suppression tuning curves, which plot the intensities of the pure tones needed to effect a given degree of suppression, as a function of tone frequency.

In the case of click-stimulated TEOAEs, the results reported by Tavartkiladze *et al.* (1994) are broadly in agreement with those of Kemp and Chum (1980). Thus, different frequency components within the emission were independently suppressed by different pure tones, with suppression of a particular CEOAE frequency requiring the least intense pure tone when the suppressor tone was at the same or nearly the same frequency. As with their click suppression data, differences in the manner of calculating and reporting the results prevent useful quantitative comparisons between these findings and those of Kemp and Chum (1980). However, an interesting feature of the results of Tavartkiladze *et al.* (1994) is the similarity in shape of their iso-suppression tuning curves to more classical

descriptions of cochlear tuning and filter shapes. Information of this sort is not available from the data presented by Kemp and Chum (1980).

The data reported by Tavartkiladze *et al.* (1994) on suppression of tone burst-evoked emissions by pure tones supported the general theme of a frequency-specific suppression effect. Hence, an emission evoked by a *burst* at a given frequency was most easily suppressed by a pure tone at the same frequency. Equivalent suppression of the same emission by a pure tone of a different frequency required an increase in the intensity of the tone. Interestingly, Tavartkiladze *et al.* (1994) presented results from one ear, in which the emission evoked by a tone burst centred at 2.5 kHz was in fact dominated by a frequency component somewhat below 2 kHz. The iso-suppression tuning curve for this TEOAE showed a corresponding spread towards lower frequencies, as compared to the curve for a TEOAE that was more confined to the frequency of the evoking tone burst. This further supported the authors' conclusion, in keeping with Kemp and Chum (1980), that individual TEOAE components originate from individual local sources distributed along the cochlea.

However, Sutton (1985) came to a markedly different conclusion based upon a very similar experiment to those of Kemp and Chum (1980) and Tavartkiladze *et al.* (1994). This author studied the suppression of a TEOAE evoked by one cycle of a 2 kHz sine wave (a click-like stimulus) by pure tones of frequencies between 1 and 2 kHz. A single ear was tested, which was stated as having a strong click-evoked OAE, but no spontaneous OAE. In keeping with Kemp and Chum (1980) and Tavartkiladze *et al.* (1994), Sutton (1985) found that suppression effects were generally strongest close to the suppressor frequency. However, he also found several "sensitive regions" in the TEOAE spectrum,

i.e. frequency components that were easily suppressed, even by suppressors of very different frequencies. Sutton concluded that this finding (particularly in the case of TEOAE components that were affected by *higher-frequency* suppressors) suggested that individual TEOAE components were generated by *distributed* rather than localised elements.

Recently, Withnell and Yates (1998) obtained findings which support those of Sutton (1985) rather than of Kemp and Chum (1980) and Tavartkiladze *et al.* (1994). These authors examined CEOAEs recorded in the presence of an ipsilateral pure tone in the guinea pig. They found no evidence of a frequency-specific suppressive effect of the type reported by Kemp and Chum (1980) and Tavartkiladze *et al.* (1994). In addition, Withnell and Yates (1998) reported occasional *enhancements* of CEOAE frequency components under the influence of the pure tone. Like Sutton, these authors concluded that individual CEOAE components are generated across a wide extent of cochlea, and thus rejected a “one-to-one” correspondence between CEOAE frequency components and generator elements. They further postulated that CEOAEs comprise significant quantities of intermodulation energy generated by interactions at various frequencies and physical locations.

Some caution may be appropriate in interpreting the findings of Withnell and Yates (1998) obtained in the guinea pig, as a general characteristic of human CEOAEs. Species differences may be particularly relevant here as CEOAEs are not as easily recorded in guinea pigs (or any non-primates) as in human ears (Zurek, 1985; Probst *et al.*, 1991). Indeed, the findings of Withnell and Yates (1998) were only made possible by their use of a novel “open ear” recording technique. Such techniques have not been

applied to the recording of human CEOAEs, and their effect on the measurements is not known. Interpretation of the findings of Withnell and Yates (1998) is further complicated by their use of the DNL technique in recording CEOAEs, rather than studying suppression of the directly-recorded (“linear”) OAE. Additionally, Ren and Nuttall (1999) offer an alternative interpretation of the enhancements reported by Withnell and Yates (1998), which does not conflict with the “one-to-one” correspondence referred to in the previous paragraph.⁵

Thus, despite the conflicting evidence reported by Sutton (1985) and Withnell and Yates (1998), the view of CEOAE frequency components being individually generated by relatively local sources within the cochlea remains, at least to a first approximation, the prevalent view of most authors. It is also supported by the findings of other workers in other types of investigations in humans (Probst *et al.*, 1986; Xu *et al.*, 1994; Prieve *et al.*, 1996) as well as in guinea pigs (Ueda, 1999).

It should be noted that a somewhat novel interpretation of the suppression effects observed by the previous authors discussed in this section was offered by Neumann *et al.* (1997). These authors obtained findings that suggested that the effect of an ipsilateral pure tone on a CEOAE is not so much to “suppress” it as to *synchronise*, or phase-lock, a portion of its energy to the tone. (This possibility had been raised, but not tested by Sutton (1985).) The subsequent cancellation of the pure tone from the averaged record therefore also

⁵ Ren and Nuttall (1999) suggest that the enhancements observed by Withnell and Yates (1998) could be accounted for by a modification of the CEOAE generation processes within the cochlea due to an impedance discontinuity induced by the pure-tone suppressor. This interpretation by Ren and Nuttall (1999) is, however, contested by Yates and Withnell (1999).

removes a portion of the CEOAE signal – the net result is then interpreted as “suppression”. Nonetheless, whether the data of the authors discussed in this section represents suppression or synchronisation, their conclusions as to the frequency specificity of CEOAE generation remain essentially unchanged.

2.4.2 Low-frequency suppressors

The TEOAE suppression by continuous signals discussed in Section 2.4.1 could be regarded as a “steady-state” suppressive phenomenon, in that the suppressors used were tones that went through many repeated cycles within the time period of each TEOAE. In contrast, a set of experiments performed by Zwicker and co-workers (Zwicker, 1983; Zwicker and Scherer, 1987; Zwicker *et al.*, 1987) investigated the changes in amplitude of TEOAEs *within a single cycle* of an intense, periodic suppressor of very low frequency. These studies were primarily motivated by an inquiry into the processes behind psychoacoustic masking, as was the study discussed in Section 2.2.2 of Gobsch *et al.* (1992). (In Zwicker’s case, however, it was simultaneous, rather than nonsimultaneous masking that was under consideration.)

These studies by Zwicker and co-workers used two different kinds of suppressor signals. In Zwicker *et al.* (1987), suppressive effects due to a 30 Hz sinusoid were examined. In Zwicker (1983) and Zwicker and Scherer (1987), the suppressors used consisted of a set of complex low frequency waveforms which were selected in order to test certain theoretical arguments (discussed below). The stimuli used to evoke TEOAEs in all three studies were short tone bursts centred at 1300 Hz. Only low-level tone bursts were used, at either 14 or 20 dB SL. In all cases, the stimulus tone bursts were presented repeatedly, at intervals that

were phase-locked to the periods of the suppressors. Further, in all cases psychoacoustic masking period patterns (MPPs) were also measured, which related the audibility of the tone bursts to their positions within the period of the low frequency suppressor (i.e. masker), for different levels of the masker. Data were reported for one ear in each study.

In the case of the study using the 30 Hz sinusoidal suppressor (Zwicker *et al.*, 1987), the authors measured TEOAEs evoked by stimulus bursts presented at two different points in time, relative to the suppressor cycle. These were at the peak of the suppressor waveform (maximum condensation of pressure) and at the trough (maximum rarefaction). In summary, the authors reported in relation to their TEOAE measurements: (a) that TEOAEs evoked at both condensation and rarefaction phases of the suppressor cycle could be completely suppressed by a suppressor of level in the vicinity of 100 dB SPL; and (b) that the rarefaction phase was more effective in suppressing the TEOAE than the condensation phase. In measuring the MPPs relating the same tone burst stimuli and the 30 Hz sinusoid as a masker, Zwicker *et al.* (1987) found striking similarities between the masking and suppression data, and concluded that the simultaneous masking they observed was an entirely cochlear phenomenon.

In Zwicker (1983) and Zwicker and Scherer (1987), the suppressors used were again low frequency periodic signals (with periods of either 140 or 300 ms), but were not sinusoidal as the authors wished to discriminate between the derivatives of the signal. They once again recorded TEOAEs evoked by stimuli presented at various points within the suppressor cycle, this time at either 25 or 32 different points within the cycle, rather than at simply the peaks and the troughs. The authors found that the TEOAEs suffered varying degrees of suppression, in a manner that varied smoothly with the position of the evoking

tone burst within the suppressor cycle. Once again, the rarefaction phase of the suppressor was more effective in suppressing the TEOAE than the condensation phase.

However, their choice of suppressor waveforms and analyses in these two studies also enabled Zwicker and Scherer to make a further important conclusion. This was that the degree of suppression of the TEOAEs, within the parameters of their studies, was largely determined by the *second derivative* of the suppressor waveform. This further led them to conclude that the degree of suppression was related to the *velocity* of the basilar membrane when excited by the low frequency suppressors (Zwicker and Scherer, 1987). As in the case of suppression and masking by a low frequency sinusoid, the authors also conclude that simultaneous masking under the conditions studied here is an entirely peripheral, cochlea-based phenomenon.

The studies of Zwicker and co-workers are unique in that of all the TEOAE suppression phenomena discussed, these are the only ones that find evidence of an influence of the polarity or phase of the intracochlear disturbances involved. However, there may be a link between these findings and the possibility of a polarity-dependent effect in click suppression speculated on by Lina-Granade and Collet (1995), and in MLS rate suppression (and perhaps in click suppression) raised by Picton *et al.* (1993).

2.5 Contralateral suppression

Although the weight of evidence suggests that the suppression of a CEOAE by additional ipsilateral stimulation primarily represents direct cochlear interactions, there remains the theoretical possibility of an involvement of the ipsilateral olivocochlear

efferent system. This arises from the documented suppressive effects of the contralateral olivocochlear efferent pathway and the existence of a parallel ipsilateral pathway. The literature on contralateral efferent suppression of CEOAEs is therefore briefly reviewed here.

Contralateral suppression of CEOAEs mediated by the olivocochlear efferent system was first reported by Collet *et al.* (1990). These authors reported a small but significant reduction in the CEOAE amplitude in one ear due to the simultaneous presentation of broadband noise in the contralateral ear. For a contralateral stimulation of 50 dB SPL, CEOAE amplitude was reduced by approximately 1 dB. Collet *et al.* (1990) conducted a number of additional measurements to rule out the possibility of middle-ear reflexes, transcranial conduction or technical artifacts causing the effects they observed. Subsequent investigations have found similar effects in patients without a middle-ear reflex, due either to Bell's palsy or to surgical section of the stapedius muscle tendon (VeUILlet *et al.*, 1991; Berlin *et al.*, 1993a). Conversely, the effect is reported as being absent in patients with acoustic neuromas, presumably reflecting an interruption of efferent nerve transmission (Maurer *et al.*, 1992; Prasher *et al.*, 1994; Maurer *et al.*, 1995). Perhaps more significantly, contralateral suppression was also reported as being absent in patients who had undergone a vestibular nerve section, a procedure which is also likely to have severed the olivocochlear efferent supply (Williams *et al.*, 1993; Williams *et al.*, 1994; Scharf *et al.*, 1994). However, in a similar study Giraud *et al.* (1995) reported that contralateral suppression was greatly reduced, but not absent, in another group of patients who had undergone a vestibular neurectomy. Thus, while an exclusively middle ear mechanism does not appear to be supported, a mixed effect

involving both acoustic reflex and olivocochlear pathways may remain a possibility in normal ears.

The amount of contralateral suppression tends to increase with increasing contralateral stimulation level (Collet *et al.*, 1990), but to *decrease* slightly with increasing ipsilateral click level (Collet *et al.*, 1994; Veuillet *et al.*, 1996). This decrease in suppression with increasing ipsilateral click level may be interpreted as an increase in the slope of the CEOAE level function under the influence of contralateral stimulation. Berlin *et al.* (1994a) reported greater suppression for the later segments of the CEOAE waveform, and emphasised the importance of examining suppression within restricted time segments.

Lind (1994) attempted to quantify the latency of the contralateral suppression effect and reported substantial variation among subjects, with onset latencies varying from “less than 40 ms to 140 ms”. In a more recent study, Hill *et al.* (1997) reported the onset latency as being between 7 and 20 ms.

Following the initial report using broadband noise, Veuillet *et al.* (1991) reported contralateral suppression using narrowband noise, as well as trains of clicks as the contralateral stimulus. In the case of narrowband noise, somewhat frequency-specific suppressive effects were observed. This frequency specificity reduced at higher contralateral stimulus levels. For contralateral trains of clicks, Veuillet *et al.* (1991) observed increasing suppression as the inter-click interval was reduced.

Berlin *et al.* (1993b) also studied contralateral suppression using narrowband noise and click trains, as well as pure tones. They found that narrowband noise was the most effective suppressor, followed by click trains, with pure tones being the least effective. In contrast with Veuille *et al.* (1991) however, no significant frequency effect was found for narrowband noise. These authors also did not alter the contralateral inter-click interval in their study.

Maison *et al.* (1997) examined the suppressive effects of contralateral amplitude-modulated pure tones. Consistent with the findings of Berlin *et al.* (1993b) above for pure tones, significant suppression was only observed when the modulation depth exceeded 75%. A degree of frequency specificity was observed in relation to the carrier frequency of the amplitude-modulated tone, in keeping with the findings of Veuille *et al.* (1991) for narrowband noise.

2.6 Issues to be investigated

A number of issues that need to be addressed can be identified on the basis of the survey of the literature above. These fall into two broad groups.

The first of these involves a detailed parametric study of the suppression of a CEOAE by a single suppressor click over a broad range of parameters, in order to characterise the phenomenon fully. Technical and measurement limitations of some past studies need to be overcome and finer analyses conducted, in order particularly to clarify issues on which discrepant results have been reported. These include findings of CEOAE enhancements and dependence of suppression upon waveform time segment.

Clarification on the issue of polarity-symmetry or otherwise of CEOAEs at small inter-click intervals, and of the suppression mechanism is also required: a polarity dependence at small inter-click intervals, as suggested by some authors, would run counter to the accepted findings for conventional CEOAEs, but would be consistent with the findings on CEOAE suppression by continuous low-frequency signals. A closer examination of the link between this type of suppression and the static nonlinearity of the CEOAE level function is required, as is a characterisation over a range of test click levels, rather than of the relative levels of the suppressor to the test click only.

A somewhat different set of issues relate to the nature of the suppression phenomenon under the influence of multiple suppressor clicks. All of the above studies on click suppression used a single suppressor click. Although a cumulative effect has been postulated in relating click suppression due to multiple suppressor clicks to the rate suppression exhibited in CEOAEs measured using the MLS technique, no experimental evidence for or against such an accumulation of suppression has been reported. Indeed, given the likelihood of nonlinear interactions between the multiple suppressors themselves, the suppression due to one suppressor may well be *reduced* by the addition of another. New experimental data are therefore required to test the hypothesis of an accumulation of the suppression due to multiple suppressors.

These issues are investigated in two main experiments. The aims, results and discussions of these experiments are presented in separate sections of the thesis. The issue of polarity-sensitivity is also important to the test paradigm developed for the main experiments – this is therefore addressed at the outset and is described prior to the main

experiments (Chapter 5). The test paradigm, equipment and analysis techniques are common to these experiments and are described in the following chapter, Chapter 3.

3. Equipment and data analysis

The experimental work in this project was divided into two main experiments, which are described in separate sections in this thesis. Whilst subjects and specific test design varied between these experiments, a largely common set of test equipment and analysis techniques were used. Elements common to both experiments are described in this chapter, whilst any methods that were specific to a particular experiment are described in the subsequent chapters along with a description of that experiment.

3.1 Measurement of temporal interactions

3.1.1 Test paradigm

The experimental paradigm used to study the phenomenon of click suppression is based on that used by Kemp and Chum (1980) and is illustrated schematically in Figure 3.1. The figure shows, in epoch (a), a pair of stimulus clicks labelled 'T' and 'S' (for 'Test' and 'Suppressor'), presented close in time and both of the same (positive) polarity. Each click evokes a CEOAE response, and the response due to the test click overlaps that due to the suppressor (and the suppressor click itself) to generate a net waveform as shown. In epoch (b) an identical pair of stimulus clicks is presented, except that here the test click is inverted in polarity. This polarity inversion produces a corresponding inversion in the polarity of the test-evoked OAE, which again overlaps that due to the suppressor and the suppressor click, to generate another (different) net waveform. The

net waveforms (including both clicks and OAEs) obtained in epoch (a) and epoch (b) are then averaged in time, but *inverting* the time record from epoch (b) as indicated in Figure 3.1. In the resultant average (c) therefore, the suppressor click and suppressor-evoked OAE are cancelled, leaving only the test click and corresponding OAE. Epochs (a) and (b) are alternated an arbitrary number of times and averaged in order to increase the signal to noise ratio of the measurement, while maintaining the correct sense of the averaging and equal numbers of epochs (a) and (b).

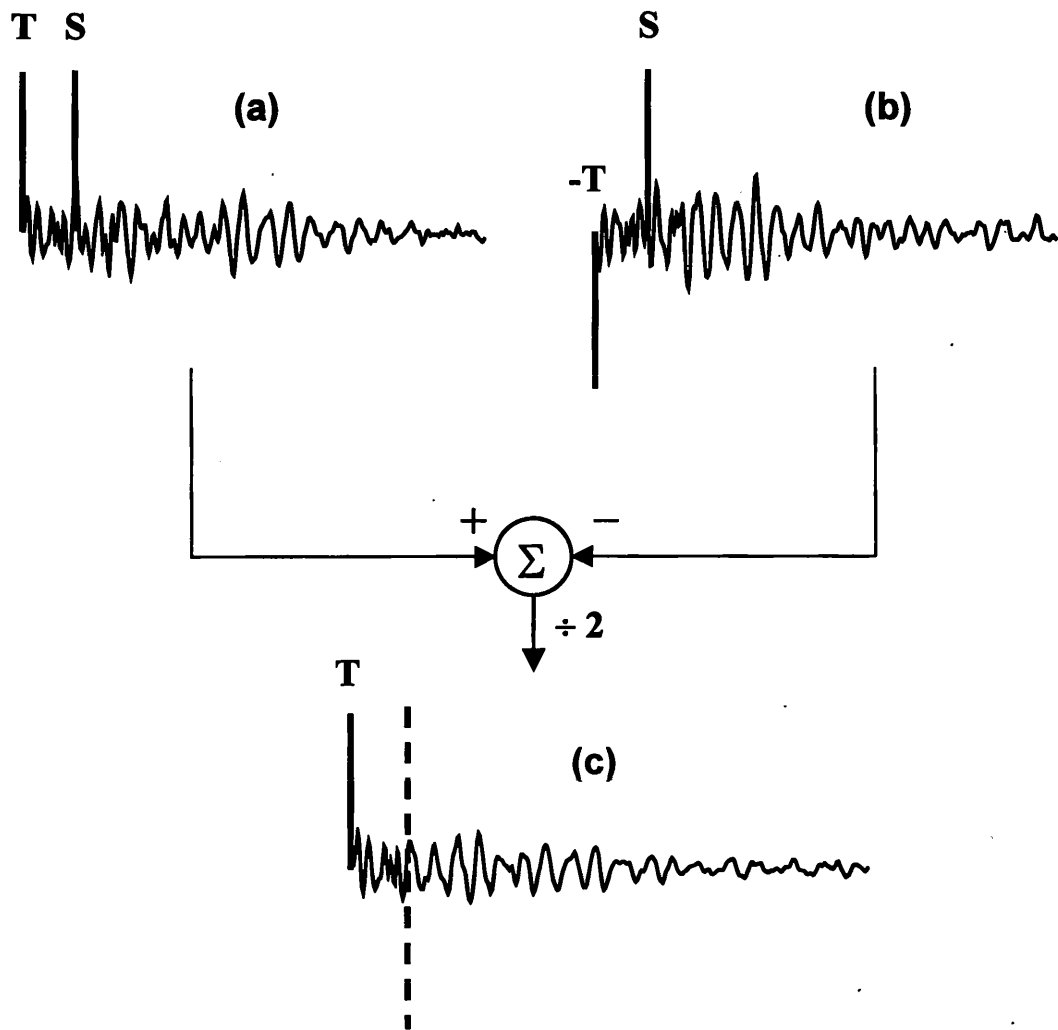


Figure 3.1. Cancellation paradigm for measurement of click suppression.

In a linear system, the OAE evoked by the test click would be unaffected by the presentation of the suppressor click, the test- and suppressor-evoked OAEs would superpose, and upon recovery of the test-evoked OAE in (c) above (the “*suppressor*” condition), an identical response to that which would have been evoked by the test click alone (the “*no-suppressor*” condition) would be obtained. Any systematic change in the test-evoked OAE measured in the *suppressor* condition relative to that in the *no-suppressor* condition therefore represents a nonlinear interaction between the test and suppressor stimuli and/or the corresponding OAEs evoked. A parametric characterisation of this nonlinear phenomenon may be obtained by measuring these changes, while varying the time interval between the test and suppressor clicks and the amplitudes of the two clicks.

These three basic parameters are represented here as L_T and L_S , the levels of the test and suppressor clicks respectively, and Δt , the time delay of the suppressor relative to the test click. Note that Δt may take a positive (as in the illustration of Figure 3.1) or a negative value, corresponding to a “following” or a “leading” suppressor respectively.

A further generalisation of the technique allows for the use of *multiple* rather than single suppressor clicks. As before, suppressor clicks and suppressor-evoked OAEs cancel and any change in the test-evoked OAE between *no-suppressor* and *suppressor* conditions reflects nonlinear interactions between the system’s responses to the multiple suppressors and to the test click. In this case these interactions are subject additionally to nonlinear interactions between the suppressors themselves.

3.1.2 System development

A customised system was developed for the implementation of the test paradigm described above and for conducting associated CEOAE measurements. This measurement system utilised the analogue (front-end) stage of the Programmable Otoacoustic Emission Measurement System (POEMS), described by Cope and Lutman (1988) and widely used in research in the UK. The analogue front-end interfaced with a commercially-available data acquisition and control module (Cambridge Electronic Design (CED) 1401plus). Both the front-end and the CED 1401plus were controlled via respective digital interfaces by a personal computer and purpose-written software, with a graphical (Microsoft Windows) user interface. This system allowed for great flexibility in the specification of stimulus sequences and in the measurement of the response, and allowed for the implementation of variations on the basic experimental paradigm, as well as subjective (click) threshold measurements and the conventional measurement of CEOAEs.

A two-channel output system was required for the click suppression measurements (discussed below). Rectangular clicks of width 100 μ s were delivered to two output transducers (Knowles BK1851 receivers) via a pair of 12-bit digital-to-analogue converters and associated driver circuitry. Click amplitudes were scaled in software. The ear canal signal measured by the microphone (Knowles EK3024) was passed through a programmable gain amplifier (controlled by the host computer) and bandpass filtered between 500 Hz and 5000 Hz within the POEMS front-end (roll-off slopes > 12 dB/octave). It was then routed to the 12-bit analogue-to-digital converter of the CED 1401plus and sampled at a rate of 20 kHz.

The sampled signal was stored in a temporary buffer in the CED 1401plus and then transferred to the host computer for averaging in the time domain. The averaging scheme implemented an overload rejection facility which eliminated raw time records that contained any sound pressure amplitudes exceeding pre-set limits, as could occur due to subject-generated noise. The remaining “good” time records (sweeps) were then averaged. (The system software ensured that equal numbers of good sweeps corresponding to epochs (a) and (b) in Figure 3.1 were averaged, as necessary for the correct implementation of the paradigm). The running average of the sampled waveform was displayed in real time during each recording, along with statistics of the total number of sweeps and number of good sweeps.

The main components of the user software interface, which was composed of a number of windows for specifying settings, controlling the external hardware and monitoring and displaying the results, are shown in Figure 3.2. Stimulus and recording parameters such as presence or absence and number of suppressor clicks, polarities of the clicks and of the averaging scheme and inter-click delays, as well as conventional CEOAE recording parameters, were freely selectable via this software interface as indicated. Note that in the case of multiple suppressor clicks, the system allowed for suppressors to be leading, following, or leading as well as following the test click.

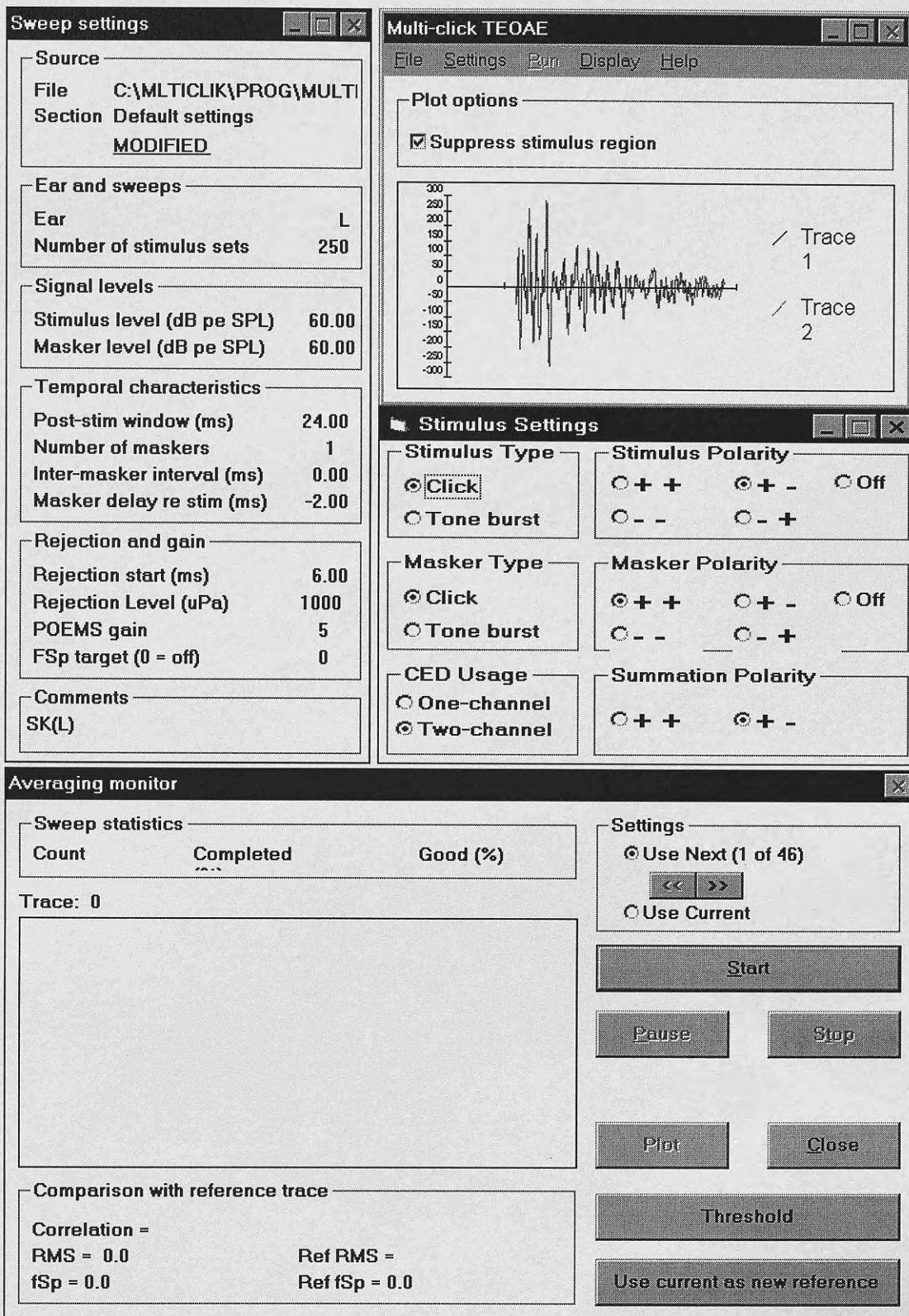


Figure 3.2. Principal components of the user software interface.

The various test parameters could be specified either by manual entry into the dialog boxes shown in Figure 3.2, or by storing parameter sets in “initialisation files” for automatic retrieval by the test software. The former method was predominantly used for system development, diagnostics and calibrations, and the latter for gathering experimental data. As large volumes of experimental data were to be generated, the automatic setting of test parameters for successive recordings within a session was essential to the feasibility of the main experiments. In practice it meant that test time was dictated only by the amount of data actually required for averaging purposes and a small overhead due to the overload rejection scheme.

Acoustic clicks and microphone output were calibrated to dB peak-equivalent (pe) SPL and μPa respectively, using a “2 cc” coupler conforming to IEC 60126 and a Bruel & Kjaer 4144 reference microphone.⁶ Sessional calibration checks of the entire system were accomplished by delivering a reference tone burst to each output transducer in turn and recording the signal measured by the probe microphone, with the probe inserted into a Grason-Stadler 0.5 ml cavity.

While the author was not responsible for the principal design of the measurement system or the development of the test software, he was responsible for designing some

⁶ The dB peak-equivalent SPL value was measured as the level (in dB SPL) of a 1 kHz pure tone with a peak-to-peak value equal to the maximum peak-to-peak excursion of the acoustic click (both pure tone and click being measured in the coupler by the reference microphone). For the system used in the present study, at the typical click rate of approximately 40/s, subjective (audibility) threshold corresponded to 25 to 30 dB pe SPL for normally hearing subjects.

key features, testing and evaluating the system and finding solutions to important technical problems.

One of the key modifications to the paradigm originally described by Kemp and Chum (1980) is the alternation here of the polarity of the *test* click and of the time-averaging; as opposed to alternation of the polarity of the *suppressor* click and of *fixed-sense* time-averaging. The two paradigms are mathematically identical (for a linear system), but the one used here gives more perfect cancellation of the suppressor click. (Any residual due to non-cancellation of the suppressor click could contaminate the test-evoked OAE record, as clear from the dotted line in Figure 3.1.) The possible influence of the polarities of the stimuli on the (nonlinear) click suppression phenomenon is examined in Chapter 5.

A second benefit of alternating the sense of the averaging of the recorded data was substantially to eliminate minor electrical artifacts in the recordings. (These were artifacts that were synchronised to the averaging time base and of fixed polarity, which were identified as being related to the transfer of data buffers between the CED 1401plus and the host computer.)

Despite the above modification to the original paradigm, a small non-cancellation artifact remained when high-level test and suppressor clicks were both delivered using the single output transducer in the standard POEMS system probe. Details of the analysis of this technical problem are described in Appendix I. In summary, exhaustive testing of the system revealed that the artifact arose due to a type of hysteresis or “memory” in the transducer, whereby the output amplitude for an intense positive click

(for a given electrical input) depended on the polarity of a *preceding* intense click. Thus two successive suppressor clicks had very slightly different amplitudes if one was preceded by a positive test click and the second by a negative one. This amplitude difference only became apparent when the test paradigm attempted to cancel the suppressors, resulting in the residual artifact. (The artifact was insensitive to the delay between test and suppressor clicks, suggesting a different “resting state” following intense positive as opposed to negative clicks.) The solution to the problem was found by employing two separate transducers for delivering the test and the (one or more) suppressor clicks, requiring the two-channel output system as described above. Thus a specially-designed ear canal probe that housed a pair of receivers as well as a microphone was developed and used – its characteristics were otherwise closely matched to that of the standard POEMS probe.

The problem of hysteresis described in the preceding paragraph is also likely to have contributed to the stimulus artifacts noted by Picton *et al.* (1993) in recording CEOAEs using bipolar MLS sequences (Section 2.3). These authors used a probe with a single receiver, and noted that their click artifacts were more troublesome for bipolar MLSs than unipolar ones. Due to the pseudo-random nature of their sequences, some of their positive clicks, for example, would have followed other positive ones and some would have followed negative clicks, as in the present study.

A further technical difficulty was encountered when testing this new ear canal probe. It was found that a small but significant drift in the amplitude of the CEOAE in the *no-suppressor* (baseline) condition was often observed, over a time-course of the order of several minutes. This drift was invariably in the direction of increasing CEOAE

amplitude, and although the *no-suppressor* amplitude was to be constantly tracked in experimental measurements⁷, it was of sufficient concern to warrant further investigation. It was determined that amplitude drift of this nature did not occur when using the original (single-receiver) probe. Further, the original probe had been constructed with a fine-bore air vent in it (as had been the normal practice when it was produced), whereas the modified probe had been constructed without such a vent. It was reasoned that the lack of the vent might cause a slight positive air pressure to result in the ear canal when the probe was inserted. Such a pressure would cause a pressure differential across the eardrum (assuming the middle-ear pressure was at or around atmospheric pressure), which would be gradually reduced as the canal pressure was released through an imperfect seal of the probe tip. As eardrum pressure differentials are known to reduce CEOAE amplitude (Naeye *et al.*, 1992), the explanation above was consistent with the direction of the baseline drift observed. A second dual-receiver probe was therefore constructed, which did incorporate an air vent. This probe was found to be free of the described drift problem and was used for all measurements in the project.

3.2 Other measurements

Pure-tone audiometry and middle-ear measurements were conducted using standard clinical equipment (Grason-Stadler GSI 16 audiometer fitted with Telephonics TDH-50 earphones, and Grason-Stadler GSI 33 middle-ear analyser).

⁷ Indeed, it was the practice of tracking the CEOAE amplitude in the *no-suppressor* condition that revealed the amplitude drift.

Conventional CEOAE measurements were carried out using exactly the same system and procedures as developed for the click suppression measurements, but by specifying in software that no suppressor clicks were to be presented.

The main system software also allowed for the measurement of click thresholds (to test clicks alone) by providing audiometric facilities for rapidly incrementing or decrementing the click level in variable step sizes, and random presentation of the click streams under mouse and keyboard control. The GSI 16 audiometer and response button were used to monitor subject responses in these measurements.

SOAEs were measured using the same probe and front-end equipment as used for CEOAE measurements. In this case, the receivers in the probe were disconnected and the filtered microphone signal routed (via the POEMS front-end amplifier and bandpass filter) to a Hewlett Packard HP3561A Dynamic Signal Analyser for spectral analysis. Spectral magnitude averaging was performed, again incorporating an overload rejection scheme to eliminate noisy measurement records, such as those due to subject movement or noise. Averaged spectra were stored within the analyser's bubble memory storage for subsequent retrieval (via an IEEE 488 interface) and analysis.

3.3 Data analysis techniques

CEOAE waveforms and SOAE spectra were analysed using purpose-written software within the DADiSP data analysis package (DSP Development Corporation). All such

analysis software was developed by the author. Higher-level, grouped and statistical analyses were performed using the SPSS statistical software package (SPSS Inc).

3.3.1 CEOAEs

All waveforms were subjected to off-line digital bandpass filtering in order to reduce the influence of noise on the waveform, prior to determination of signal amplitudes. (As noted below, the ultimate limit on CEOAE suppression measurable was determined by the level of noise in the waveforms.) A 196-point finite impulse response (FIR) filter (designed using in-house software) was used, with roll-offs exceeding 40 dB/octave, stop-band attenuation exceeding 80 dB and cut-off frequencies of 400 and 7000 Hz. (The predominant frequency content of adult CEOAEs is accepted as being well within this region – e.g. Probst *et al.*, 1991.)

In analysing these CEOAE waveforms, the segment from 6 to 24 ms was taken as the “whole waveform”. Earlier parts of the time record are dominated by the test click itself and (depending on test click level) by the ringing of the test click, rather than the CEOAE. Where appropriate, analyses were also performed on smaller time-segments of the measured waveforms, but unless otherwise stated, results presented are based on the amplitudes of whole waveforms.

In general, a pair of replicate waveforms was recorded for every CEOAE measurement made in this project. In the case of click suppression measurements, a pair of replicate *no-suppressor* waveforms and a pair of replicate *suppressor* waveforms were obtained for each *suppressor* condition. For each pair of replicate waveforms, an estimate of the

CEOAE signal was taken as the *average* of the two waveforms, and the estimate of noise in the waveforms as the *difference* between the replicate waveforms divided by two.

The RMS amplitudes of these signal and noise estimates were initially computed in 1-ms slices within DADiSP. These were then combined as needed in SPSS to give RMS amplitudes in arbitrary time-segments (see Appendix II).

Unless otherwise stated “suppression” was always calculated as the ratio expressed in dB of the RMS amplitude (in a given waveform time-segment) of the CEOAE signal in the *no-suppressor* condition to that in the corresponding *suppressor* condition. Thus a reduction in CEOAE amplitude due to the presence of a suppressor is indicated by a positive value of suppression. In many instances of the *suppressor* condition, the amplitude of the OAE was limited by the noise, i.e. the OAE was suppressed into the noise floor (in at least some part of the waveform). A “suppression ceiling” was therefore also defined, as the ratio in dB of the CEOAE signal in the *no-suppressor* condition to the amplitude of the estimate of waveform *noise* in the *suppressor* condition.

3.3.2 SOAEs

SOAE amplitude spectra were converted from the internal data format of the Dynamic Signal Analyser into text files with appropriate header information for import into DADiSP. Within DADiSP individual SOAEs were identified objectively using software routines developed for the purpose.

The “raw” spectrum was first smoothed using a 64-point moving average in order to obtain a baseline level that was a relatively free of variations in the noise floor, but followed the system’s frequency response as evident in the recorded spectrum. An SOAE was then identified as any peak in the raw spectrum that exceeded the baseline at that frequency by at least three standard deviations (of the raw spectrum).

4. Model of click suppression based solely on level function

nonlinearity

Although Kemp and Chum (1980) proposed a model of click suppression based on a static, compressive nonlinearity, none of the subsequent investigators of click suppression appear to have extended their original investigations in this regard. The present work attempts to do so. In this chapter a simple phenomenological model of click suppression, based solely on the compressive nonlinearity of the CEOAE level function, is described. This model is in some respects more simplified than that of Kemp and Chum (1980). However, as will be seen, it is adequate for the purposes of comparing the experimental data described in the following chapters. It is also shown in this chapter that the key features of the model are not altered by increasing its complexity in a variety of ways.

4.1 General considerations

Previous sections have described the click suppression phenomenon and its measurement paradigm, which seeks to measure the influence on the CEOAE (evoked by a test click) of the presentation of an additional suppressor click. The proximity of the two clicks is important and a complete parametric characterisation of the phenomenon requires that the time delay between test and suppressor clicks (Δt) be made positive as well as negative. A special condition arises when $\Delta t = 0$, and in particular when the test and suppressor clicks are also equal in level ($L_T = L_S$).

Figure 4.1 shows the basic test paradigm (previously described in Section 3.1) under these particular conditions.

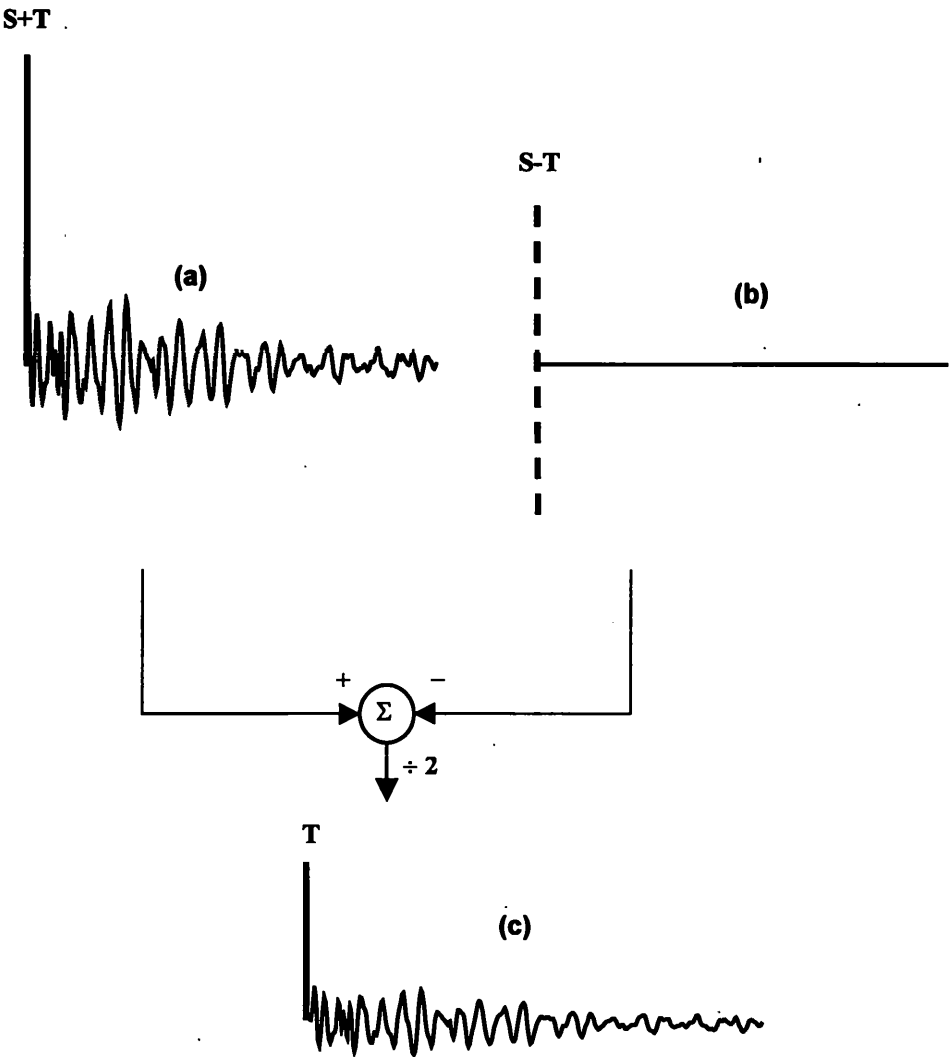


Figure 4.1. Suppression paradigm with $\Delta t = 0$ and $L_T = L_S$

Referring to Figure 4.1, in epoch (a) now, the net stimulus consists of a *single* click of amplitude twice that of the test click (or level $L_T + 6.02$ dB), and a single OAE is

evoked. In epoch (b), the two stimulus clicks of equal and opposite amplitude cancel, giving zero net stimulus and therefore zero response. (These discussions of signals in epochs (a) and (b) assume an ideal measurement system and ignore background noise.) The time-averaging of the responses in epochs (a) and (b) now simply results in a halving of the waveform measured in epoch (a). Any “suppression” measured in this condition is entirely a reflection of a compressive nonlinearity in the basic CEOAE level function. If the level function were linear (i.e. had a slope of 1 dB/dB), the effective doubling of the test click amplitude in epoch (a) would result in an OAE of twice the amplitude of that in the *no-suppressor* condition. The subsequent time-averaging (division by two) would then yield an OAE identical to that in the *no-suppressor* condition, i.e., no suppression would be measured. In fact, if the basic CEOAE level function has a slope of m dB/dB⁸, then it can be shown (see Appendix III) that the suppression (in decibels) measured in the case of equilevel test and suppressor clicks and $\Delta t = 0$ is given by

$$supp = 6.02(1 - m) \quad \dots \text{Eqn. 4.1}$$

It can thus be seen that the phenomenon of click suppression may be entirely derived from the nonlinearity of the CEOAE level function in the special case of $\Delta t = 0$. The argument may further be extended to conditions of *non-zero* inter-click intervals, if allowance is made for a finite (non-zero) response duration at the response generator site. Nominally distinct stimuli may thus generate responses that overlap at the point of

⁸ The slope of a level function in dB/dB is a convenient measure of the degree of static nonlinearity as previously discussed, and is widely used to characterise the nonlinearity of cochlear processes.

nonlinearity. It is therefore possible that the “temporal nonlinearity” evidenced by the click suppression phenomenon previously reported (even when $\Delta t \neq 0$) arises entirely from the static amplitude nonlinearity of the level function, coupled with a non-zero response duration of the generator elements.

This possibility is investigated by using a simple mathematical model to derive suppression that would be obtained for non-zero inter-click intervals, under the above assumption of a suppression mechanism that is entirely derived from the compressive CEOAE level function, which in turn reflects the static nonlinearity of the underlying I-O function. The predictions of suppression arising from I-O nonlinearity are presented as a function of Δt to permit subsequent comparison with the pattern of suppression actually obtained in real-ear measurements, to be described in Chapter 7.

For simplicity, a “localised” CEOAE generation process is assumed (see Section 2.4) and behaviour in a single frequency channel, or by inference, at a single spatially-constrained site on the BM is simulated. A generalisation to the expected suppression pattern in the ear canal (which arises from the combined output of multiple channels) may be made by assuming that the nonlinear effects *within* frequency channels simulated here dominate over any nonlinear effects *between* channels.⁹

The simulation of suppression due to I-O function nonlinearity then involves three steps:

(i) Specification of an appropriate nonlinear I-O function.

⁹ This assumption is justified by the majority of the experimental data on CEOAEs in humans, as discussed in Chapter 2. Its implications for the present study are discussed further in Section 8.3.

(ii) Choice of an appropriate set of stimulus (input) functions. (At this point the level function for the I-O and input functions chosen may also be derived.)

(iii) Application of pairs of instances of the input functions to the I-O function, and measurement of the influence of one input on the other.

These mathematical descriptions do not attempt to represent the physical elements of the biological system faithfully, and the choice of functions and associated parameters is somewhat arbitrary. However, relatively simple functions have been chosen and, as discussed below, the resultant suppression pattern is not particularly sensitive to these choices.

4.2 Specification of nonlinear I-O function

The compressive nonlinearity of the I-O function is modelled by a power function of the form

$$y = Ax^m \quad (0 < m < 1) \quad \dots \text{Eqn. 4.2}$$

This is one of the simplest types of compressive I-O functions and further, as

$$\log(y) = \log(A) + m\log(x),$$

the corresponding level function (on log-log axes) describes a straight line, with a slope of m dB/dB.

The power function specified in Equation 4.2 does suffer from the minor mathematical drawback of being undefined for negative values of the input, x . However, this is easily overcome as described in the following discussions.

Figure 4.2 shows an instantaneous I-O function of the form $y = x^{0.5}$ (defined for positive x values and mirrored about the origin.) This I-O function corresponds to a compressive level function with a slope of 0.5 dB/dB, a value typically observed in CEOAE level functions.

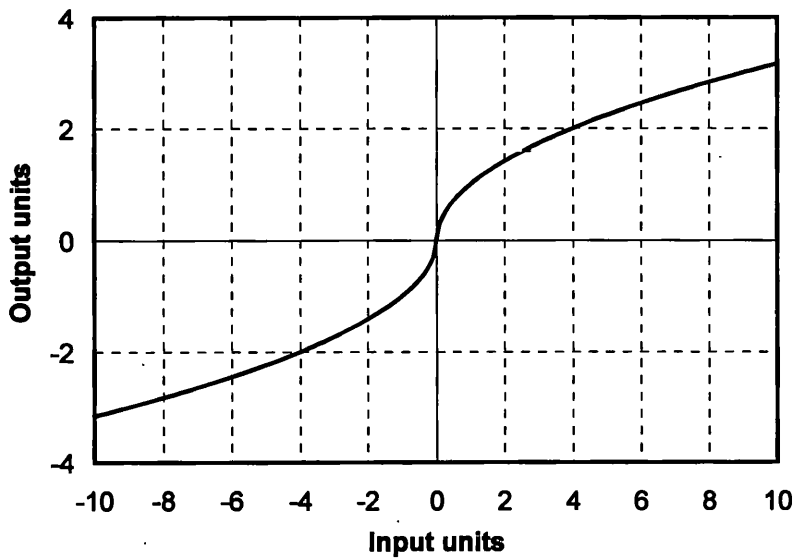


Figure 4.2. Compressive I-O function defined by $y = x^{0.5}$.

4.3 Choice of input functions and system response for single inputs

As the model of suppression pertains to a single frequency channel, the clicks that form the “test” and “suppressor” inputs in the experimental paradigm are replaced here by tone bursts. (In accordance with conventional modelling of the mechanics of the cochlea, the excitation due to a click is regarded as being filtered by a narrow band-pass filter at a given site on the BM.) For the purpose of this exercise, tone bursts were generated by applying a Hanning window to 10 cycles of a 1-kHz sinusoid of unit amplitude. The nonlinear behaviour of the system is then demonstrated by applying scaled versions of this tone burst, or pairs of instances of it, to the I-O function described by Equation 4.2.

Figure 4.3 shows the input and output of the system of Figure 4.2 for a single input tone burst of amplitude 10 units. (For this and all other calculations of the output of the system, the output for a negative input is obtained by raising the absolute value of the input to the exponent m and inverting the result.) The compressive nature of the system is clearly evident from the two traces, not so much in the reduction in amplitude of the output burst, but in the distortion of its waveform.

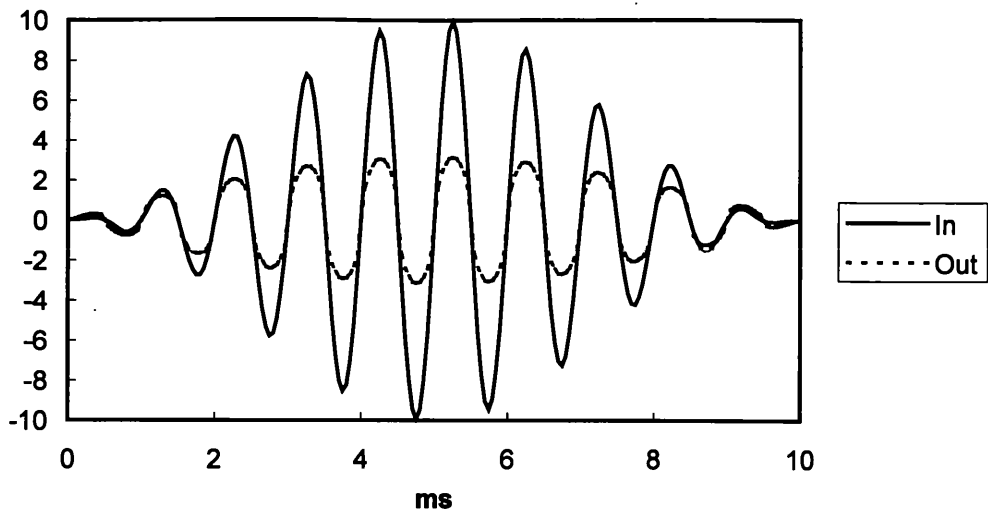


Figure 4.3. System input and output for single tone burst.

Level functions corresponding to the I-O functions of the form of Equation 4.2 may be generated by successively applying scaled versions of the excitation tone burst to the I-O functions and measuring the amplitudes of the outputs generated. A set of such level functions, for $A = 1$ and for different values of the I-O exponent (m), is shown in Figure 4.4. The values of m used vary between 1 (completely linear I-O function) and 0.2 (highly compressive I-O function). By definition, these values of m also equal the slopes (in dB/dB) of the level functions generated, as can be verified in the figure.

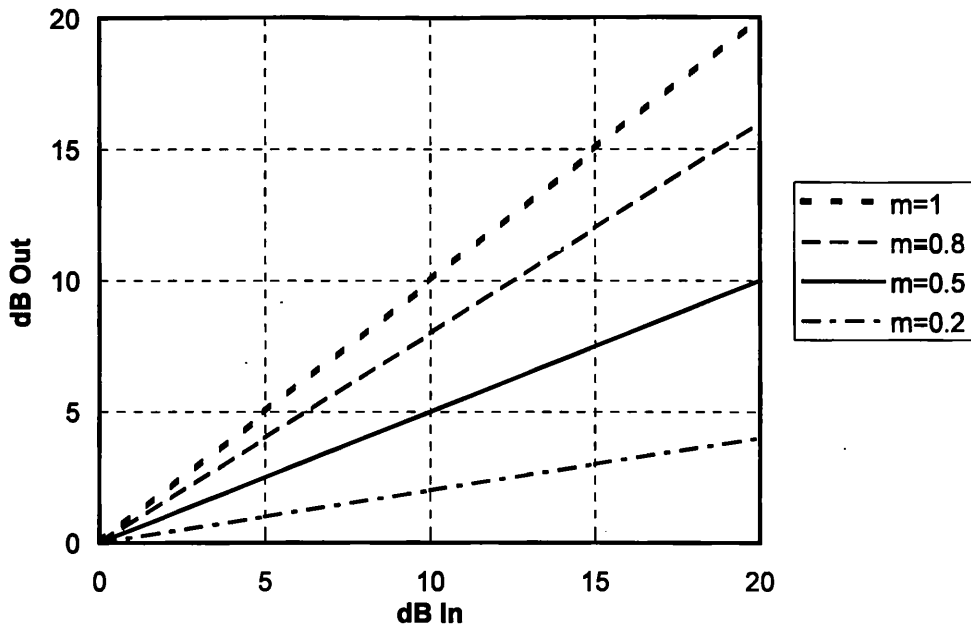


Figure 4.4. Level functions generated by application of single tone bursts to I-O functions of form $y = Ax^m$, for different values of m . $A = 1$ in each case.

4.4 Influence of one input on the output due to another

For the simulation of click suppression, the system output to a single input applied in isolation needs to be compared to the system output to the same input *in the presence of* a second such input, in a completely analogous manner to the experimental paradigm described in Chapter 3.

Thus the steps involved in making the above comparison are:

- (i) Designate a pair of instances of the excitation tone bursts as 'T' and 'S' (for 'Test' and 'Suppressor'), with a defined delay (' Δt ') between them.

- (ii) Calculate the system output waveform for an input of 'T' alone (the *no-suppressor* condition).
- (iii) Calculate the system output waveforms separately for inputs of ('S' + 'T') and ('S' - 'T').
- (iv) Subtractively average the two output waveforms from (iii) above in time to obtain the output in the *suppressor* condition.
- (v) Compare the RMS amplitudes of the outputs in the *no-suppressor* and *suppressor* conditions. As before, were the system linear the two RMS amplitudes would be identical. Any reduction in the amplitude of the signal recovered (by the above paradigm) in the *suppressor* condition over that in the *no-suppressor* condition is designated "suppression".

Figure 4.5 shows the output of the system of Figure 4.2 for a single tone burst of amplitude 10 units and the system output obtained (as at step (iv) above) for a pair of identical tone bursts with Δt set to *zero*. (The "*No-suppressor*" output here is the same as the "Out" trace in Figure 4.3). As can be seen, both outputs are distorted by the nonlinearity. However, the output recovered by the cancellation paradigm described (*suppressor* condition) is smaller than that due to the single tone burst (*no-suppressor* condition). In fact the ratio of RMS amplitudes measured (suppression) corresponds to 3.01 dB, as expected from Equation 4.1 for a level function slope of 0.5 dB/dB and $\Delta t = 0$.

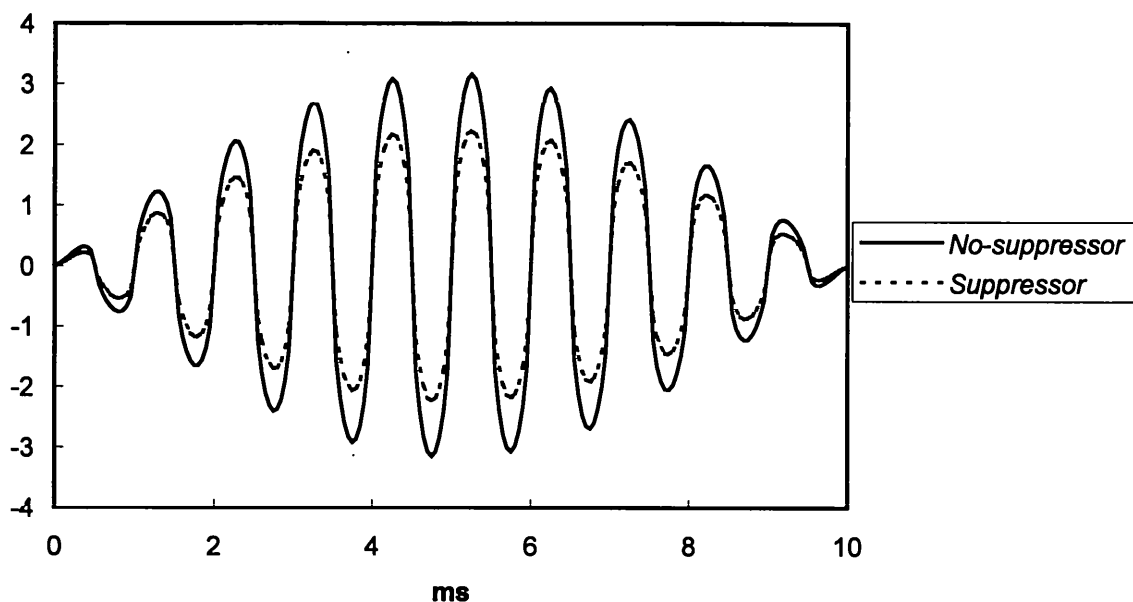


Figure 4.5. System outputs for the *no-suppressor* condition and for the *suppressor* condition with delay (“ Δt ”) equal to zero.

The same procedure was then applied repeatedly to pairs of tone bursts of the same amplitude, each time varying Δt in 1 ms steps from -10 to $+10$ ms, to generate a curve of suppression in dB versus Δt . This curve (for the compressive nonlinear system with an I-O exponent, m , of 0.5) is shown as the solid line in Figure 4.6. The curve shows a peak at $\Delta t = 0$ (at the value of 3.01 dB). Figure 4.6 also shows the variation in suppression generated by different degrees of I-O compression. The additional lines in the figure plot the suppression obtained (versus Δt) for a range of different values of m . (The curve for the linear I-O condition of $m = 1$ is a horizontal line at 0 dB suppression.)

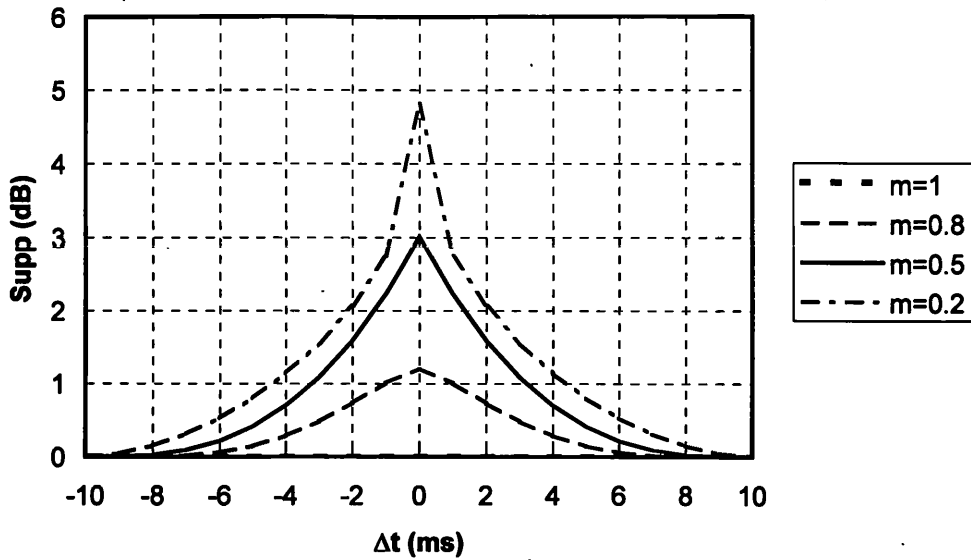


Figure 4.6. Suppression arising entirely from nonlinearity of an I-O function of form $y = Ax^m$, plotted as a function of Δt . Four curves are shown, for different values of $m \leq 1$, with $A = 1$ in each case.

The curves of Figure 4.6 represent the desired pattern of click suppression generated by a model that assumes a suppression mechanism based entirely on a compressive CEOAE I-O function. These simulated patterns of suppression are further subject to the assumption of the model that the nonlinear effects within frequency channels (or BM sites) dominate over any nonlinear effects between channels. The simulations confirm that significant suppression can arise from a static nonlinear I-O function when excited by nonsynchronous (but overlapping) signals. Comparing the curves, it can be seen that the amount of suppression progressively increases at all points on the curve as the exponent m decreases (indicating an increasing degree of nonlinearity). In each case the peak of the curve occurs at $\Delta t = 0$, with a value at this point equal to that dictated by Equation 4.1 and the I-O exponent m . The amount of suppression then reduces monotonically as Δt increases in either direction. Note however, that the symmetry of

the curve about $\Delta t = 0$ is entirely due to the choice of a tone burst with an envelope that is symmetric about its maximum as the excitation function (see e.g. input waveform in Figure 4.3). This aspect of the simulation would not necessarily apply to real-ear measurements of CEOAE suppression, even if it were entirely I-O function-based. Similarly, the convergence of the simulated suppression curve to 0 dB as Δt approaches ± 10 ms arises from the arbitrary choice of a burst duration of 10 ms and is not intended to represent the extent over which the actual suppression of CEOAEs would occur.

Although the simulation presented is subject to the constraints of the assumptions made and the mathematical functions chosen to represent the phenomenon, all of the features described in the above paragraph are also demonstrated if a compressive I-O function described by an appropriate polynomial expression is chosen instead of that of Equation 4.2. (The power form of Equation 4.2 is preferred for this illustrative model as it is simpler and gives a direct link to the slope of the level function in dB/dB.)

Identical curves are also obtained if the function representing the system nonlinearity (Equation 4.2) is modified to incorporate a time delay (corresponding to a phase shift).

The key features of the suppression curves, i.e. the peak positions and the values at the peaks, are also insensitive to a number of more complex elaborations of the simple model described and the input functions used. These include:

- (i) The use of an *asymmetrically* compressive I-O function, modelled by specifying two different values of the exponent m for positive and negative inputs respectively. (In that

case, the suppression value at the peak is approximately given by using the mean of these values of the exponent in Equation 4.1.)

(ii) An effective shift of the “operating point” of the I-O function from the point of maximum slope (as in the above discussions) to a point further along the curve.

(iii) The use of tone bursts with *asymmetric* envelopes (which may be more physiologically representative) as the basic excitation function, rather than the symmetric one of Figure 4.3.

(iv) The use of more complex “double-lobed” excitation function, rather than the simple “single-lobed” tone bursts illustrated in Figure 4.3. Such “double-lobed” responses have been noted in some relatively recent reports of basilar membrane responses to clicks (e.g. de Boer and Nuttall, 1997; Recio *et al.*, 1998). Their effect in the model described here is to introduce lower-amplitude secondary peaks in the suppression curves, however the position and magnitude of the primary peak at $\Delta t = 0$ remain unchanged.

Finally it should be noted that the model described is insensitive to the polarities of the signals applied in the cancellation paradigm – identical results are obtained using the original experimental paradigm of Kemp and Chum (1980) and that used in the present study. (This is to be expected from the symmetry of the describing functions and was confirmed here.)

5. Preliminary experiments

5.1 Effects of polarities of test and suppressor clicks

In reviewing the literature relevant to this study in Chapter 2, the question of a “symmetry in polarity” in relation to CEOAE suppression was encountered in several different contexts. Two main issues arose in examining the work of previous authors:

(i) A technical problem of a lack of an exact match in the amplitudes of the inverted clicks encountered by Kemp and Chum (1980) and by Picton *et al.* (1993) (in the use of bipolar MLS clicks sequences). Aside from the non-cancellation artifacts generated by the mismatch of stimuli, a potential complication arises from the possibility of the lack of an exact match in the amplitudes of the *CEOAEs* evoked (and in the suppression generated) by such mismatched clicks.

(ii) A physiological question as to whether the widely-accepted polarity symmetry of conventionally-measured CEOAEs (described in Section 2.1) also holds under conditions of very short inter-click intervals. This may alternatively, and more generally, be regarded as whether the click suppression phenomenon itself is sensitive to the polarities of either test or suppressor clicks. This possibility was suggested, but not examined, by Lina-Granade and Collet (1995) in relating the mechanism of the click suppression they measured to a possible hair cell adaptation phenomenon. It was also suggested by Picton *et al.* (1993) in noting changes in CEOAE response morphology at high click rates, when using bipolar MLS sequences as compared to unipolar ones.

However, the effect observed by Picton *et al.* may well have been due to the polarity-related nonlinearities in their experimental equipment acknowledged by the authors, and mentioned in (i) above. Finally, the possibility of a polarity-dependence of click suppression is raised by the findings of Zwicker and co-workers (Zwicker, 1983; Zwicker and Scherer, 1987; Zwicker *et al.*, 1987), who found that the rarefaction phase of an intense low-frequency periodic signal was more effective in suppressing TEOAEs than the compression phase (see Section 2.4.2).

While the technical issue described in point (i) above was dealt with in the development and the testing of the system and discussed in Chapter 3, experimental data needed to be obtained in order to address point (ii). It was further necessary to do so at the very outset of the study in order, strictly, to validate the experimental paradigm (both of this study and of similar previous ones¹⁰) and in order to justify comparisons between the present study and the previous ones. This is further explained below with the aid of a schematic illustration of various click presentation paradigms.

Figure 5.1 illustrates a series of variants of the paired-click presentation paradigm described in Chapter 3, in which the polarities of the test (T) and suppressor (S) clicks and the sense of the averaging of each of epochs (a) and (b) are varied as indicated. For

¹⁰ Note that neither Kemp and Chum (1980) nor Lina-Granade and Collet (1995) addressed this issue in the checks they performed. The former authors established that the (*conventionally-spaced*) suppressor-evoked CEOAEs substantially cancelled under suppressor inversion (despite measurably imperfect suppressor click cancellation). Similarly, Lina-Granade and Collet (1995) established that conventionally-spaced clicks of alternating polarity and the CEOAEs they evoked cancelled into the noise floor in their experimental setup.

the purpose of this illustration, suppressor clicks are always shown following the corresponding test clicks.

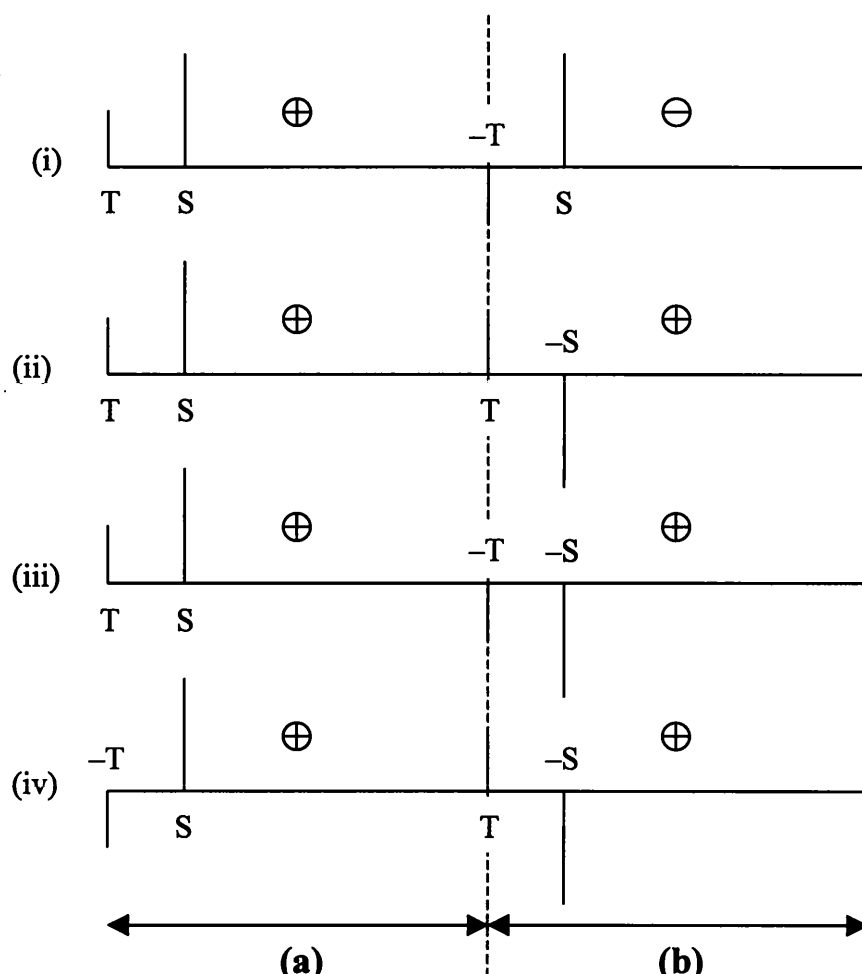


Figure 5.1. Four variations on the paired-click presentation paradigm used in this and related studies. The polarities of test (T) and suppressor (S) clicks and the sense of the averaging, i.e. positive (\oplus) or negative (\ominus), within each of epochs (a) and (b) are indicated.

Panel (i) at the top of Figure 5.1 shows the basic paradigm used in the present study and described in Chapter 3 (Figure 3.1). As indicated here, test clicks are positive in

epoch (a) and negative in epoch (b), suppressor clicks are positive in both epochs, and epoch (b) is subtracted from epoch (a) in the averaging procedure. The suppressive action of the positive suppressor on the positive test click in epoch (a) may be denoted as $supp_{(+ on +)}$. Similarly, the suppression by the positive suppressor of the CEOAE evoked by the negative test click in epoch (b) is denoted $supp_{(+ on -)}$.¹¹

Panel (ii) of Figure 5.1 illustrates the test paradigm originally described by Kemp and Chum (1980), and also utilised by Lina-Granade and Collet (1995). In this case, the suppressive action in epoch (a) is again denoted $supp_{(+ on +)}$, while that in epoch (b) is this time $supp_{(- on +)}$. Note the corresponding inversion of the sense of averaging of epoch (b) between panels (i) and (ii).

The question that arises in the application of the measurement paradigm illustrated in panel (i) is whether or not

$$supp_{(+ on +)} = supp_{(+ on -)}$$

and correspondingly, in panel (ii), whether

$$supp_{(+ on +)} = supp_{(- on +)}$$

¹¹ The inherent presence of a reverse suppression effect of “test on suppressor” is allowed for in these discussions but not explicitly mentioned, for the sake of clarity.

Neither of these questions can be answered directly. While an equality of suppression may be assumed in both cases based upon the striking polarity-symmetry of CEOAEs at conventional click rates, the findings and suggestions of previous authors indicate the need to test this assumption. This was done by means of the presentation paradigms illustrated in panels (iii) and (iv) of Figure 5.1.

In both panels (iii) and (iv), test as well as suppressor clicks are inverted between epochs (a) and (b), with a positive sense of averaging in both epochs. Complete cancellation of the signals here would occur if both pairs of clicks and CEOAEs exactly invert. Complete cancellation here would also indicate an equality of *suppressive effects*: i.e., in the case of panel (iii)

$$supp_{(+ \text{ on } +)} = supp_{(- \text{ on } -)}$$

and in panel (iv)

$$supp_{(+ \text{ on } -)} = supp_{(- \text{ on } +)}$$

Note further that this result from panel (iv) would also directly confirm the validity of comparing results obtained using the paradigm of the present study, shown in panel (i), and of the previous authors, shown in panel (ii). (Compare epochs (b) in these two panels, which respectively describe the two sides of the equation above.)

A short series of measurements was therefore made to assess the degree of cancellation obtained using the “full-cancellation” paradigms of panels (iii) and (iv) above. Two

normal ears (from two different subjects) exhibiting clear CEOAEs were used. Two measurement runs were performed for each ear and each full-cancellation paradigm, one using equilevel test and suppressor clicks and the second using a relatively low test click level and a relatively high suppressor click level. A sample of negative and positive suppressor-test click intervals (Δt) was chosen, composed of representative values to be used in the main study. These click levels and inter-click intervals are shown in Table 5.1.

L_T (dB pe SPL)	L_S (dB pe SPL)	Δt (ms)
60	60	-5, -2, 0, 2, 5, 10
50	70	-5, -2, 0, 2, 5, 10

Table 5.1. Levels of the test and suppressor clicks, and inter-click intervals used to test each of the “full-cancellation” click paradigms.

A pair of replicate waveforms was recorded for every condition, in order to assess the presence of any residual (incompletely cancelled) signal, in the presence of the background random noise. Each waveform recorded was based on 500 consecutive averages. A minimum 24 ms recording window was used between each test click and the end of the averaging epoch (see Figure 5.1).

Figure 5.2 shows the waveforms obtained from one of the ears tested, using both the full-cancellation paradigms and for click levels of $L_T = L_S = 60$ dB pe SPL.

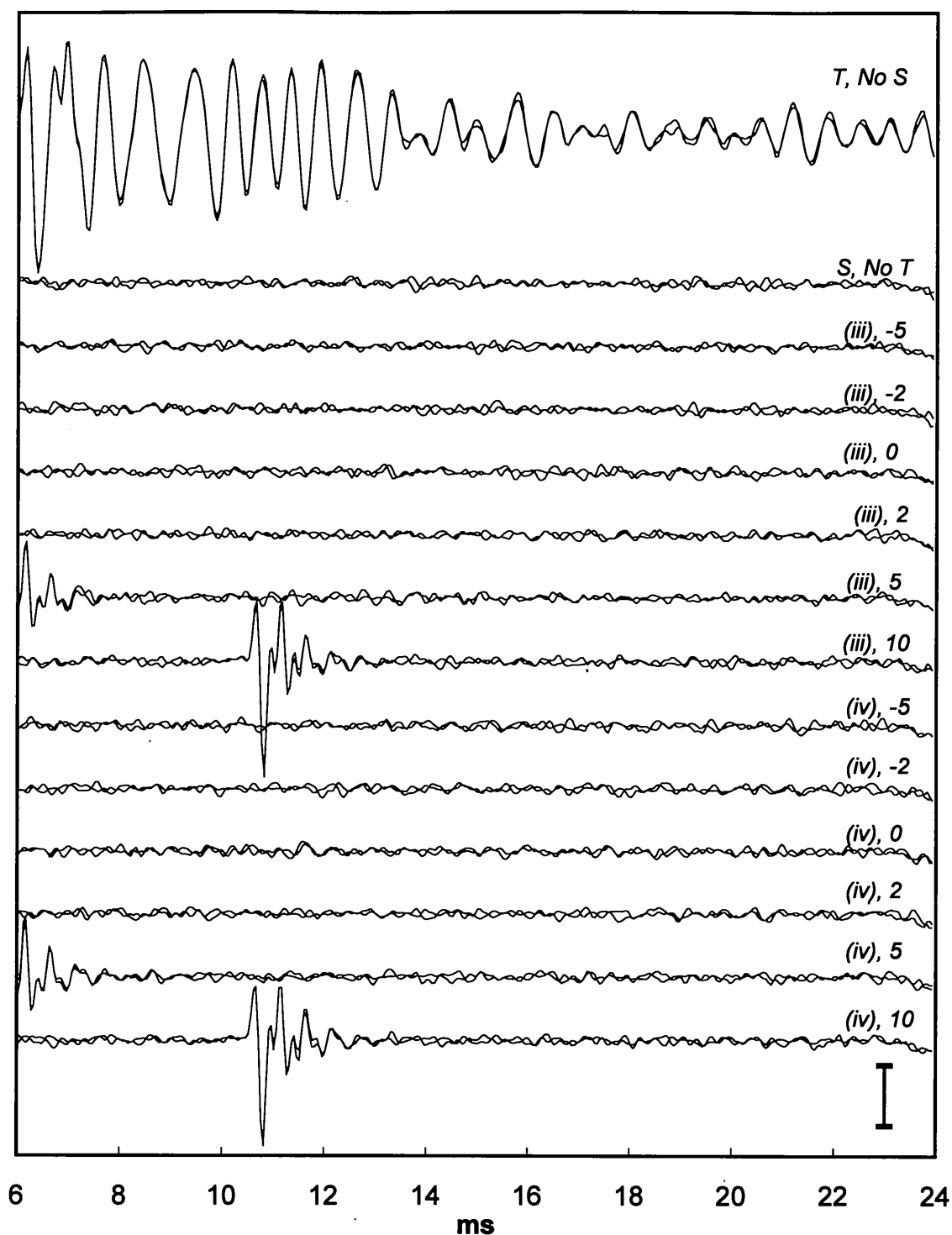


Figure 5.2. Replicate waveform pairs recorded from one ear, demonstrating the cancellation of CEOAEs at short inter-click intervals under both full-cancellation paradigms discussed in the text. Waveform pairs are labelled according to the paradigms illustrated in Figure 5.1 and the Δt value used. Also shown are conventionally-recorded CEOAEs due to test clicks alone (topmost pair), and the averaged responses due to alternating polarity suppressor clicks alone, presented at a conventional rate (second pair from top). The scale bar indicates 200 μPa .

The figure shows fourteen pairs of waveforms (with replicate waveforms overlaid), which have been offset for display purposes. The replicate waveforms at the top of the figure show for reference the conventional CEOAE response, obtained by presenting the test clicks alone. The following pair show the responses obtained when *suppressor* clicks of alternating polarity are presented alone. This waveform pair indicates cancellation of the suppressor-evoked CEOAEs to below the measurement noise floor, as previously demonstrated by Lina-Granade and Collet (1995) (and to a lesser extent by Kemp and Chum (1980)).

The following six waveforms pairs in Figure 5.2 show the responses obtained for the full-cancellation paradigm illustrated in panel (iii) of Figure 5.1, for the six respective values of Δt listed in Table 5.1 above. Similarly, the final six waveform pairs show the responses obtained for the cancellation paradigm illustrated in panel (iv) of Figure 5.1 for the same six values of Δt . Apart from an obvious click artifact for Δt values of 5 and 10 ms (discussed below), in all cases, the replicate waveforms once again show no evidence of any correlated or reproducible signal above the measurement noise. This confirms that for these click polarities and values of L_T , L_S and Δt , the polarity-symmetry of CEOAEs is preserved at short inter-click intervals, both in terms of response amplitudes and suppressive mechanisms. Specifically, it is confirmed that the suppressive action of a positive suppressor on a positive test click is equal to that of a negative suppressor on a negative test click, and that the suppressive action of a positive suppressor on a negative test click is equal to that of a negative suppressor on a positive test click. It is emphasised that this equality of suppressive actions applies to both the magnitude and the fine temporal patterns of the suppressive effects. Were there to be any significant differences in the temporal patterns of suppression in these data, then

complete cancellation of the waveforms as observed would not occur, despite an equality in the magnitude of suppression.

A clear artifact due to imperfect cancellation of the suppressor click is evident in Figure 5.2, in cases where the presentation of the suppressor click lies within or close to the time window displayed (Δt values of 5 and 10 ms). The artifact occurs due to the use of a paradigm here in which both epochs (a) and (b) are averaged additively. These artifacts were absent in the averaging paradigm used for the main experiments (described in Chapter 3), in which the sense of averaging was inverted in successive epochs. (It was necessary to use an additive averaging paradigm for the measurements in this section, as it was the cancellation of inverted *clicks* that was specifically to be investigated.)

Essentially identical results were obtained from the second ear when tested as described in the preceding paragraphs, and from both the ears when tested in a similar manner using $L_T = 50$ and $L_S = 70$ dB pe SPL.

These findings were taken as sufficient confirmation of the polarity-symmetry at short inter-click intervals that is assumed implicitly in the test paradigm described in Chapter 3, and that is necessary for unqualified comparisons between the findings obtained using this paradigm and that used by previous authors (Kemp and Chum, 1980; Lina-Granade and Collet, 1995).

The findings also indicate that the click suppression phenomenon is polarity-insensitive, and that the alternation of click polarities would not “augment” the amount of

suppression generated, as suggested by Lina-Granade and Collet (1995). Furthermore, it follows that the changes in CEOAE response morphology at high click rates observed by Picton *et al.* (1993) were more likely to have been due to equipment nonlinearities and/or artifacts, rather than physiological reasons. Finally, these findings are in contrast to the observations of Zwicker and co-workers that the rarefaction phase of an intense low-frequency periodic signal was more effective in suppressing TEOAEs than the compressive phase. This suggests that click suppression as measured in the present study and suppression of the type described by Zwicker and co-workers are not simply related.

5.2 Effects of physical interactions between signals

Theoretically, the click suppression paradigm described in Chapter 3 is sensitive only to *nonlinear* interactions between the closely-spaced clicks and/or the CEOAEs they evoke. This is because the cancellation technique removes one component (suppressor click and CEOAE) of a complex signal, leaving behind the other (test click and CEOAE). If each of these two components has no influence on the amplitude of the other and sums exactly with it (obeying linear superposition), no change in the test-evoked CEOAE should be observed. In other words, assuming that the purely physical interactions (including phase cancellations) that would occur between the two sets of clicks and CEOAEs within the ear canal are linear, they should not result in any suppression being measured.

It is not possible to test the effects of purely physical, linear interactions between genuine CEOAEs because of the inherently nonlinear nature of these responses. A

series of recordings was therefore made to measure the effects of interactions between a CEOAE and a *simulated* CEOAE, represented by a low-level tone burst generated within the ear canal. For these recordings, the standard click-pair paradigm described in Chapter 3 (also illustrated in panel (i) of Figure 5.1) was used. However, the test clicks were not presented to the ear canal, but were used instead to repeatedly trigger a 1 kHz tone burst, which was then delivered to the canal in place of the test click via one transducer of the two-channel output system. The suppressor clicks were delivered to the ear canal in the normal manner, via the second output transducer. The tone bursts were of 8 ms duration, commencing at approximately 7 ms following the trigger click, and their amplitudes were set to approximate those of a typical large-amplitude CEOAE, having a peak-to-peak value of approximately 400 μPa in the ear canal.

The arrangement described was designed to measure the effects of physical interactions in the ear canal between a low-level signal simulating the test-evoked CEOAE on the one hand, and the suppressor clicks and suppressor-evoked CEOAE on the other. Assuming that such interactions (and the behaviour of the test system) were linear, the simulated CEOAE as measured by the probe microphone would be unaffected by the presence of the suppressor clicks and associated CEOAEs.

In order to test for any possible effect, the maximum suppressor click level available on the system (80 dB pe SPL) was used for these recordings. Recordings were made for four “suppressor” conditions, with the simulated CEOAE presented in all four: no suppressor click presented, suppressor presented at $\Delta t = +5$ ms, suppressor at $\Delta t = +10$ ms, and finally no suppressor again. The first of these values of Δt resulted in a suppressor click shortly before the tone burst, leading to an overlap between the

suppressor-evoked CEOAE and the simulated CEOAE. For $\Delta t = +10$ ms, the suppressor click was approximately in the middle of the burst, and overlap would be largely between the click itself and the simulated CEOAE. Two replicate recordings were made for each of the four conditions. Recordings were made in two normal ears.

It should be noted that the triggered tone burst generator did not allow for alternating polarity tone bursts to be generated (as would exactly simulate the test-evoked CEOAEs in the experimental paradigm). Tone bursts were therefore only triggered by the first (positive-going) test click in the pair, and were only present in epoch (a), but not in epoch (b) of the presentation paradigm (see Figure 5.1). Further, as the responses in both epochs were averaged together, the resulting amplitude of the recorded tone burst was half that of the true amplitude in the ear canal.¹²

It was also recognised that the design for this experiment relied on a lack of measurable (intracochlear) suppression of the suppressor-evoked CEOAE by the simulated “test” CEOAE. This was particularly relevant as the tone burst and the suppressor CEOAE would be jointly present in averaging epoch (a), but not in epoch (b) of the presentation paradigm. However, any suppressive effects of the tone bursts on the suppressor CEOAEs were considered unlikely due to the extremely low amplitude of the bursts (which corresponded to approximately 5 dB SL at the repetition rate used).

¹² Had the (unipolar) tone bursts been delivered in *both* averaging epochs, they would have cancelled in the final recording (due to the alternating sense of the averaging used), which would have prevented an assessment of their “suppression”, if any. On the other hand, a *fixed* sense of averaging would have resulted in poorer suppressor click cancellation (as previously described), which would again have interfered with an accurate measurement of the simulated tone burst in the “suppressor” condition.

Figure 5.3 shows, from top to bottom, the four pairs of waveforms recorded sequentially in one of the ears tested. As in Figure 5.2, waveform pairs have been offset for display purposes. The RMS value of the *average* of each replicate pair, calculated for the waveform segment from 7 to 16 ms only, is indicated above it.

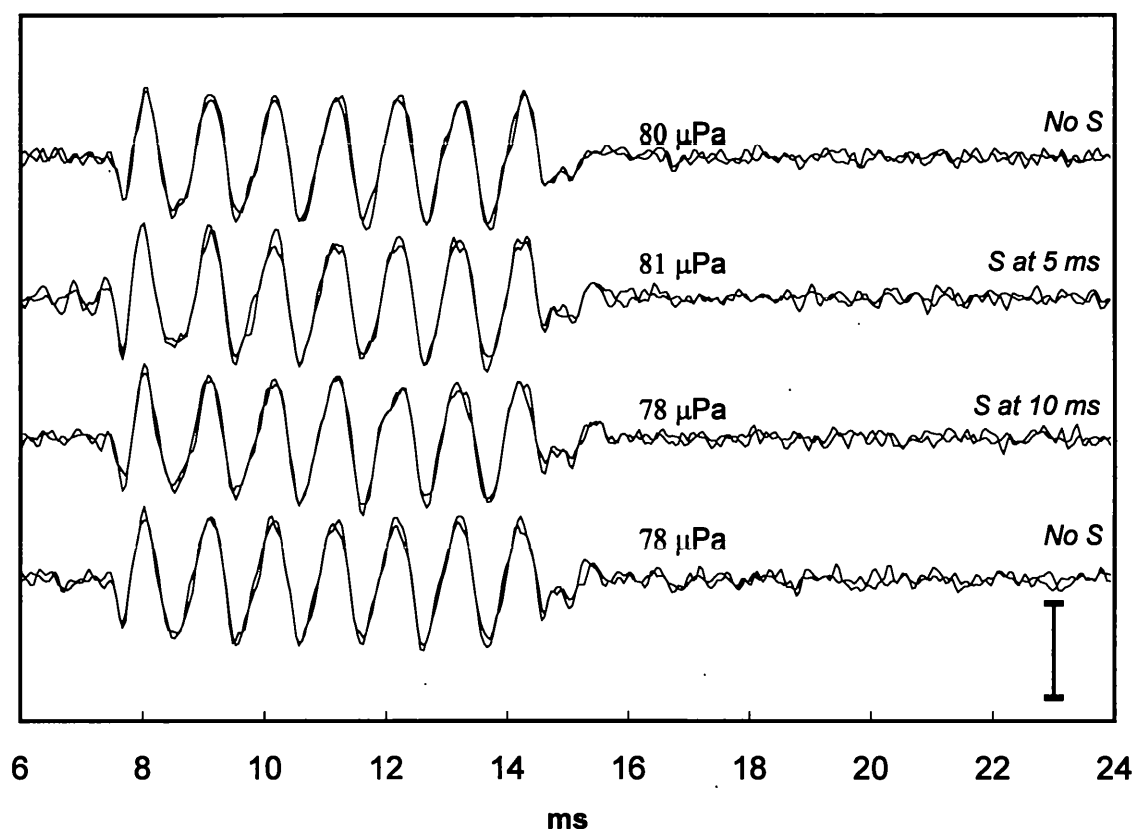


Figure 5.3. Replicate waveforms pairs recorded in one ear, investigating effects of physical interactions between a simulated “test” CEOAE (1 kHz tone burst) and a suppressor click and corresponding CEOAE. Waveforms pairs from top to bottom represent conditions of no suppressor, suppressor at 5 ms, suppressor at 10 ms, and no suppressor respectively. Also indicated above each waveform pair is the RMS value of the *average* waveform in the 7-16 ms time segment. The scale bar represents 200 μPa .

Figure 5.3 indicates that there is no detectable difference (other than due to random noise) between any of the simulated CEOAE waveforms recorded in the presence or absence of the suppressor clicks and associated CEOAEs. The RMS amplitudes of the average of the replicate tone bursts are all within 3 μ Pa of each other: this variation may be entirely attributed to the background noise evident in the recordings. (Note that the halving of the amplitude of the tone burst due to its presentation in one epoch only also results in a halving of the signal to noise ratio that would have been obtained had the burst been presented in both epochs.)

Figure 5.3 also illustrates that alternating the sense of the averaging of epochs (a) and (b) as per the standard averaging paradigm for the present study (panel (i) of Figure 5.1) results in no measurable artifact due to non-cancellation of the suppressor clicks. This is despite the fact of the unusually high-level suppressors used in this experiment (80 dB pe SPL) and is in contrast with the results shown in Figure 5.2 (for which experiment fixed-sense averaging needed to be used).

Essentially identical results were obtained in testing the second ear used for these measurements.

These results confirm that the purely linear waveform and phase interactions that would occur in the ear canal (and within the recording system) between CEOAEs evoked by test and suppressor clicks could not result in “suppression” as measured in the main experimental paradigm. The fact that these physical interactions do not influence the

recovered “test” signal also further confirms the linearity of the experimental set-up. These findings also validate the assumption (for this particular experiment) that the tone bursts presented to the ear canal simulating “test” CEOAEs would not themselves measurably suppress the suppressor-evoked CEOAEs generated within the cochlea.

Experiment One – Detailed parametric description of single-click suppression

6. Aims and methods – Experiment One

6.1 Aims

Experiment One aimed to characterise the suppression of a CEOAE by a single suppressor click by means of a detailed parametric study conducted over a broad range of parameters. The findings reported by previous authors were to be extended and discrepancies between some of these findings investigated. An explanation of the cochlear mechanisms underlying click suppression was to be sought – in particular, a resolution of the issue as to whether or not the static CEOAE level function nonlinearity was sufficient to account for the phenomenon.

6.2 Subjects

Subjects were normally-hearing young adults aged between 18 and 30. Written informed consent was obtained from all subjects, who were paid for participating in the study. As many properties of CEOAEs are significantly similar between left and right ears of any one subject (e.g. Probst *et al.*, 1986; Bonfils *et al.*, 1988; Johnsen *et al.*, 1988) only one ear per subject was used, in order to obtain an independent data set. Data were obtained from a total of 12 ears (5 from females) following exclusions based on the criteria described below.

Pure-tone air-conduction hearing threshold levels (HTLs) in the test ear were required to be ≤ 15 dB at all audiometric frequencies between 250 and 8000 Hz. Ear canals needed to be free of obstruction and middle-ear pressures (MEPs) needed to be within ± 50 daPa. Acoustic reflex thresholds (ARTs) of ≤ 100 dB HL were required (using ipsilateral, 1 kHz tone burst stimuli). Subjects with strong synchronised spontaneous otoacoustic emissions (SSOAEs) were excluded for reasons discussed below. Finally, in order to be able to measure suppression of a CEOAE, it was necessary that each ear exhibited a measurable CEOAE at the lowest level of test click to be used. The cross-correlation value for the 6 to 16 ms waveform segment (r_{6-16}) between the replicate CEOAE waveforms was used for this purpose. Ears were excluded from the study if the value of r_{6-16} for a test click level of 40 dB pe SPL was < 0.5 .

The exclusion of subjects with strong SSOAEs was based in part on reports in the literature (e.g. Zwicker, 1983; Probst *et al.*, 1986; Gobsch and Tietze, 1993; Kulawiec and Orlando, 1995) of a complex influence of SSOAEs on CEOAE responses. It is possible that subjects with strong SSOAEs represent a distinct subgroup within the normal population, with respect to the general properties of their CEOAEs.¹³ Preliminary data obtained from such subjects also indicated less uniform patterns of click suppression, compared with the data from subjects without strong SSOAEs. It is further noted in this regard that Tavartkiladze *et al.* (1994) observed an atypical pattern of suppression in the one subject out of five in their study reported as having an SOAE (see Section 2.2.1). (SOAEs in their study were actually measured using a

¹³ Some of the characteristic distinctions between SSOAEs and “true” CEOAEs have been referred to in Section 1.2. In addition, SSOAEs do not exhibit the variation of the degree of nonlinearity of the level function with waveform time segment referred to in Section 2.1.

synchronisation technique, and should therefore strictly be regarded as SSOAEs as described here.)

The exclusion criterion for SSOAEs was based on a spectral analysis of the standard CEOAE waveform obtained at the lowest test click level of 40 dB pe SPL. Subjects were excluded if this spectrum contained a sharp peak that was 10 dB or more clear of the rest of the spectrum. In all such cases, it was additionally confirmed that the record of the standard (“unsynchronised”) SOAE measurement also showed a strong peak at or very near this frequency, i.e. that the SSOAEs identified were true “synchronised SOAEs” and not simply dominant, sharply tuned CEOAE responses (see Wable and Collet, 1994).¹⁴

6.3 Test procedures

All subjects answered a detailed questionnaire concerning hearing status on the day of testing and on audiotically-relevant medical and family history. Otoscopy was performed to ensure ear canals were free of obstruction or injury. Tympanometry, acoustic reflex measurement and pure-tone audiometry were performed following standard clinical procedures.

¹⁴ Data from one other ear that gave highly (and atypically) non-uniform results were also excluded. This atypical pattern of results was most likely due again to SSOAEs. This ear also showed some evidence of an SSOAE, though not sufficient to meet the exclusion criterion for this measure.

Subjects were screened for SOAEs in the frequency range 400 to 6000 Hz, split into seven frequency spans of 800 Hz each. After allowing the subject time to settle, the HP 3561A signal analyser's auto-range function was used to set the input range maximum to approximately twice that of the input signal. Overload rejection was then used to eliminate relatively noisy measurement records (those that caused a full-range input to the signal analyser). Two replicate measurements of eight RMS (spectral) averages each were obtained at each frequency span and the data stored within the instrument's memory for subsequent off-line analysis by computer.

Subjective click thresholds were measured using click streams consisting of the test clicks alone, with a 24 ms inter-click interval. Click streams of variable duration (approximately one to three seconds) were presented manually and subjects asked to depress the response button when the clicks commenced and to release it when they ceased. Thresholds were measured to 5-dB resolution using a manual up-down protocol, along the lines of conventional pure-tone audiometry.

CEOAE level functions were also measured using streams of test clicks at a 24 ms inter-click interval. Level functions were obtained in decreasing 5-dB steps, from click levels of 70 dB pe SPL to 40 dB pe SPL. The system overload (noise) rejection limits were set for each test individually, at a level that would reject about 5% of all the raw time records. Two replicate measurements of 500 "good" sweeps were made at each level.

Click suppression measurements were then carried out, using test and suppressor clicks of levels 40, 50, 60 and 70 dB pe SPL. These gave 16 possible pair-wise combinations of click levels. However, pilot measurements had shown that suppression was generally

of minimal magnitude when the suppressor click level (L_S) was 20 dB (or more) lower than the test click level (L_T). Thus, to cut down on test time the three such level conditions in the original 16 were not used – i.e. ($L_T = 60$ dB, $L_S = 40$ dB), ($L_T = 70$ dB, $L_S = 40$ dB) and ($L_T = 70$ dB, $L_S = 50$ dB). Testing at each of the 13 remaining combinations of click levels constituted a “session” of the click suppression measurements. Within each such session, the delay of the suppressor click relative to the test click (Δt) was varied from -24 ms to $+12$ ms, in 25 steps. (All descriptions of delays and averaged waveform time axes here are with reference to the presentation of the test click, which is always taken to occur at time $t = 0$.) The values of Δt were not uniformly spaced within the above limits, but were most finely spaced in the regions of most interest as indicated by the pilot measurements.

Table 6.1 indicates these experimental values of the three basic test parameters, L_T , L_S , and Δt , used in this study.

L_T (dB pe SPL)	L_S (dB pe SPL)	Δt (ms)
40	40, 50, 60, 70	$-24, -12, -6, -5, -4, -3,$
50	40, 50, 60, 70	$-2.5, -2, -1.5, -1, -0.5,$
60	50, 60, 70	$0, 0.5, 1, 2, 3, 4, 5, 6,$
70	60, 70	$7, 8, 9, 10, 11, 12$

Table 6.1. Values of the three basic parameters used in characterising click suppression. L_T and L_S denote levels of the test and suppressor clicks respectively and Δt the delay of the suppressor relative to the test click. (The same 25 values of Δt applied to all 13 combinations of L_T and L_S .)

The time window for CEOAE measurements always extended from the leading click in the epoch (test *or* suppressor) to at least 24 ms following the test click. Further, a minimum delay of 24 ms (based on pilot measurements) was always maintained between the following click in one epoch and the leading click in the next, in order to minimise interactions between such clicks.

As with the level function measurements, the system overload (noise) rejection limits were set at a level that would reject about 5% of all the raw time records and each measurement consisted of the average of 500 “good” sweeps (i.e. 500 test clicks).

Replicate measurements of the CEOAE in *suppressor* and *no-suppressor* conditions were made. Furthermore, each replicate pair of *suppressor* measurements was bracketed within a pair of *no-suppressor* measurements, in order to track small changes between the two conditions. This bracketed or “semi-interleaved” testing protocol afforded considerable savings in test duration over a fully interleaved design, whilst still providing an accurate and contemporaneous reference condition for each *suppressor* condition.¹⁵ As a result, 76 CEOAE waveforms were recorded in each suppression measurement session (corresponding to fixed values of L_T and L_S , and 25 different

¹⁵ In a design that fully interleaved *suppressor* and *no-suppressor* conditions, each pair of *suppressor* replicates would have been preceded by a pair of *no-suppressor* replicates. The use of a semi interleaved design does mean that successive pairs of replicates in the *no-suppressor* condition are not fully independent, as the second replicate in one pair is also used as the first replicate for the next pair. The implications of this effect of the semi-interleaved design are addressed in the following chapter.

values of Δt .) The test parameters for the 76 successive recordings within a session were set automatically, using information stored in an initialisation file. The 76 averaged waveforms so recorded were monitored visually during testing and stored to disk for subsequent analyses.

All measurements described above, with the exception of the middle-ear tests, were conducted with the subject seated comfortably within a sound-isolated booth, with the tester and measurement system outside the booth. Subjects were in visual contact with the tester and were asked to avoid swallowing and to remain as still and relaxed as possible while recordings were made. In the case of CEOAE measurements, the on-line display of the running average of the sampled waveform was also visible to the subject, in order to provide immediate visual feedback of the degree of noise generated by movement, swallowing, etc.

Execution of the 13 click suppression measurement sessions and other associated procedures typically took a total of approximately 10 hours for each subject, spread usually over three days. Administration of the questionnaire section pertinent to the day of testing, otoscopy, tympanometry and measurement of CEOAE level functions were repeated at the beginning of each separate day of testing. All other procedures were conducted once only.

7. Results – Experiment One

Figure 7.1 shows a sample set of waveforms obtained from one of the click suppression measurement sessions from a single ear, for a test click level of 60 dB pe SPL and suppressor click level of 70 dB pe SPL. The figure serves to illustrate some of the quantitative results that are presented in the subsequent sections. Waveforms are shown over the 6-24 ms time window, corresponding to the “whole CEOAE waveform”. Although replicate recordings in the *suppressor* condition were bracketed between replicate recordings in the *no-suppressor* condition, for the purpose of this illustration a single replicate pair of *no-suppressor* waveforms is shown as the top pair of traces, followed by replicate *suppressor* waveforms at various values of inter-click delay, Δt , as marked in the figure.

Following the waveform pairs from top to bottom, no clear effects on the waveforms are evident until $\Delta t = -4$ ms, at which point the waveforms are suppressed over their entire extent. At $\Delta t = 0$ the CEOAEs appear to be almost entirely suppressed into the noise. At $\Delta t = 4$ ms there is an apparent *enhancement* of the waveform around 12 ms and substantial suppression after 14 ms. At $\Delta t = 12$ ms the waveforms appear largely unaffected until about 18 ms and (partially) suppressed after that.

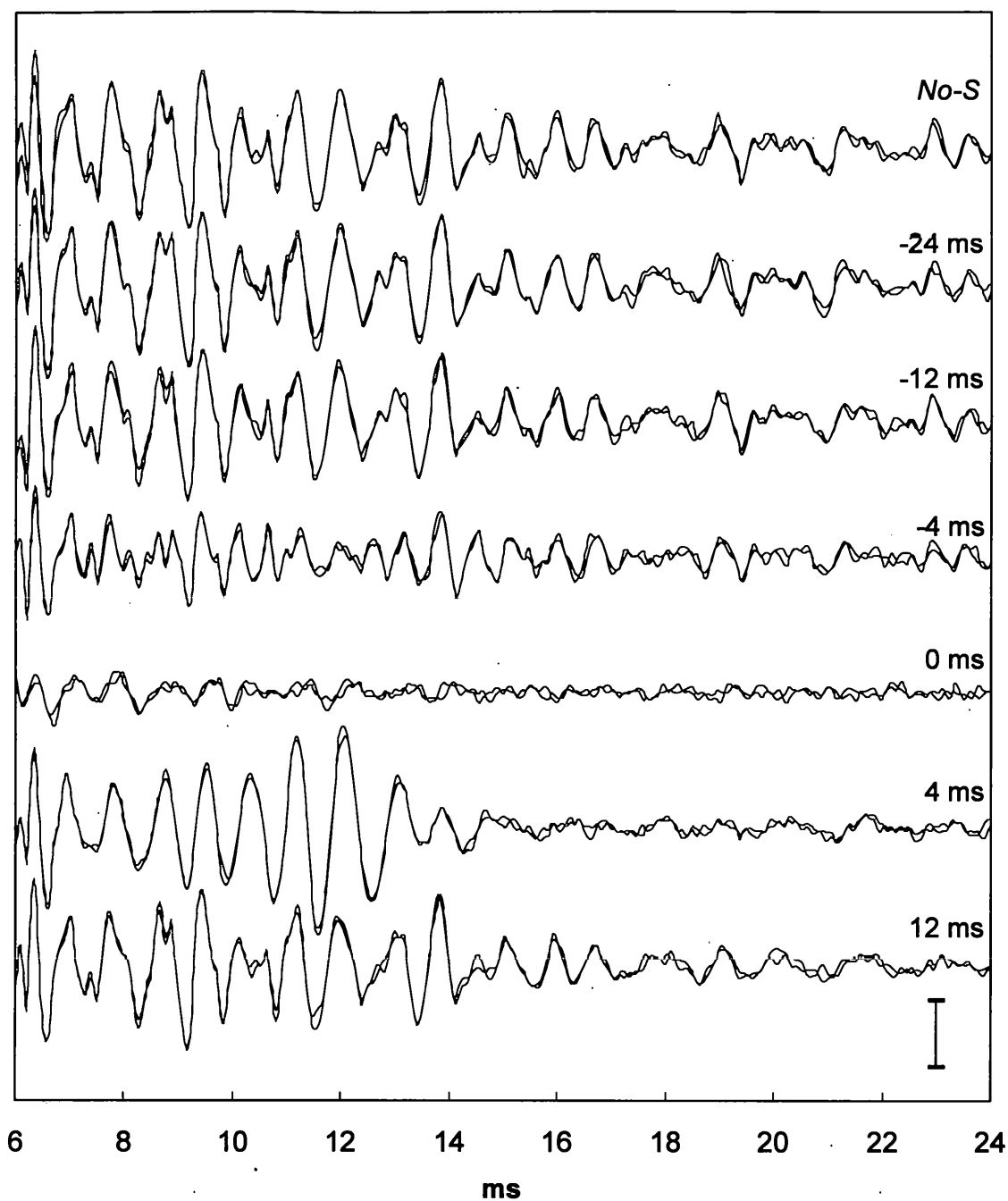


Figure 7.1. Replicate CEOAE waveform pairs in the *no-suppressor* (top pair of traces) and *suppressor* conditions at values of Δt as marked. Data are from a single test session, with $L_T = 60$ dB pe SPL, $L_S = 70$ dB pe SPL. The scale bar indicates $200 \mu\text{Pa}$.

The suppression phenomenon was characterised in this experiment as a function of three primary parameters (independent variables): the levels of the test and suppressor clicks (L_T and L_S respectively) and the inter-click delay (Δt). One “derived” parameter of considerable importance is the relative level of the two clicks ($L_S - L_T$). Similarly, the primary measures (dependent variables) in the experiment are the amplitudes (or levels) of the CEOAE signal and noise estimates, while the most important derived measure is “suppression” as previously defined (Section 3.3.1). These measures themselves are defined for particular segments of the CEOAE waveform – waveform segment therefore comprises a fourth independent variable. As plots of all dependent variables as functions of all four independent variables would not be practical or easy to interpret, the main results are presented below in the most basic and instructive format, which is also the format in which suppression generated by the model of Chapter 4 was presented. Additional representations of the data are shown in the subsequent sections, in order to highlight or discuss different aspects of the results.

Prior to the examination of the effects of the primary test parameters, the influence of other extraneous variables on the measured suppression is considered below.

7.1 Influence of between-subjects variables on suppression

The influence of various test and control variables on the whole-waveform suppression measured was examined by a repeated measures analysis of variance (implemented in SPSS under the GLM family of procedures), including within- and between-subjects factors. As expected, suppression is highly sensitive to the primary parameters chosen for the experiment (within-subjects factors) described above. These effects are

discussed in detail in subsequent sections. By contrast, no significant effects upon suppression were detected due to any of the following between-subjects factors – sex, ear, age, mean HTL or ART.

Similar tests were conducted separately on the data for each of the 13 suppression measurement sessions (for the 13 combinations of L_T and L_S), to test for any influence of the *no-suppressor* (baseline) CEOAE amplitude upon the measured suppression. A significant effect of the baseline CEOAE amplitude was found in five of the 13 cases. These were for the level combinations of $L_T = 40$, $L_S = 50, 60, 70$; $L_T = 50$, $L_S = 70$; ($p < 0.01$ in all 4 cases) and $L_T = 70$, $L_S = 70$ dB pe SPL ($p < 0.05$). In the first four cases, which are for the two lowest values of L_T , a positive relationship between baseline amplitude and measured suppression was found. This is consistent with a limiting effect of the noise floor upon the suppression obtained – CEOAEs of larger baseline amplitude are less affected by the noise floor and larger suppression values can be measured. In the case of $L_T = 70$, $L_S = 70$ dB pe SPL, a (weak) *negative* relationship between baseline amplitude and measured suppression existed, i.e. CEOAEs of smaller amplitude showed more suppression. The effect in this case may be related to the degree of compression of the CEOAE – a greater degree of compression would tend to give both a lower baseline amplitude at the highest click level and a greater amount of suppression.

7.2 Effect of “semi-interleaved” design on measurement sensitivity

While the main results presented and discussed in the present study consist of large and highly significant effects, in some cases (e.g. in delimiting the extreme boundaries of the

suppression effects) it is necessary to establish the significance of relatively small changes in CEOAE amplitude. The interleaving of *no-suppressor* and *suppressor* conditions in the CEOAE measurements results in high measurement sensitivity, in that relatively small suppression values test as significant, using standard statistical tests. However, this apparent sensitivity is qualified by the fact that successive *no-suppressor* measurements are not based on independent measurements in the “semi-interleaved” experimental design described in Chapter 6.

An independent estimate of measurement sensitivity was therefore obtained, based upon the changes in the CEOAE amplitude between alternate (rather than successive) *no-suppressor* estimates, which are independent of each other. The difference in dB between alternate *no-suppressor* CEOAE amplitude estimates within each measurement session was therefore calculated for all the data obtained in this experiment. Figure 7.2 shows the distribution of these differences, which is normal with a mean of 0 dB and standard deviation 0.3 dB. (Note that the corresponding distributions for each of the 12 subjects studied are similar to the overall distribution shown here.) Using a criterion of two standard deviations, a suppression value of ± 0.6 dB was therefore established as the minimum value that may be regarded as valid (when considering mean data) in the present study. This value is used in conjunction with other tests of significance where appropriate in the following discussions.

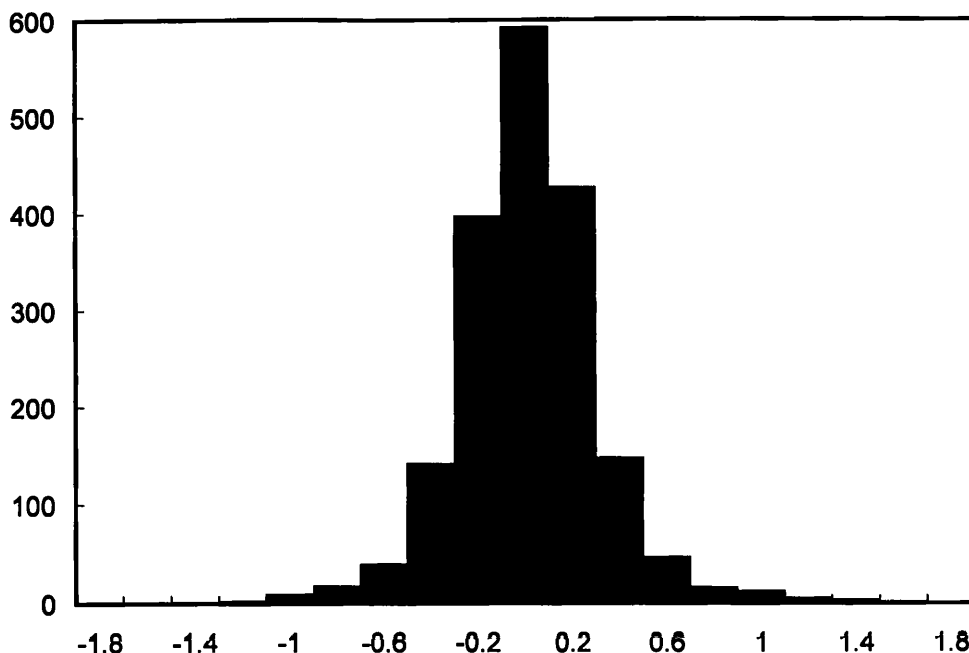


Figure 7.2. Histogram of differences in dB between successive *independent* pairs of *no-suppressor* CEOAE amplitudes within each measurement session. Data are for the whole CEOAE waveforms (6-24 ms segments).

7.3 Effects of primary test parameters on suppression

7.3.1 Whole-waveform measures

The most useful representation of the click suppression as measured in this experiment is probably as a function of inter-click delay (Δt), for various values of test and suppressor clicks (L_T and L_S) and of the waveform segment. Figure 7.3 (a) and (b) show examples of such plots for a single subject, calculated for the waveform time segment from 6 to 24 ms (the “whole waveform”) and for $L_T = L_S = 60$ dB pe SPL. In

Figure 7.3(a) the levels of the CEOAE and of the noise in each of the *no-suppressor* and *suppressor* conditions are plotted versus Δt . Figure 7.3(b) is derived from the same data and plots the actual amount of suppression versus Δt .

Figure 7.3(a) shows firstly that the CEOAE level in the *no-suppressor* condition (upper solid line) shows little variation (within ± 0.25 dB) around about 12 dB SPL when tracked across the duration of the test session. However, the level in the *suppressor* condition (upper dashed line) is reduced at Δt values greater than about -12 ms, with a minimum of about 6 dB SPL at $\Delta t = -2$ ms. The noise levels in both conditions (lower pair of lines) are of the order of -8 dB SPL and show no systematic variation with Δt .

Figure 7.3(b) plots the measure of most interest from the same data, which is the difference between the two curves of CEOAE level (upper lines) in Figure 7.3(a). Note therefore that small variations or drift in the *no-suppressor* CEOAE level are compensated for in this measure of suppression. Plots of the sort of Figure 7.3(b) allow the best visualisation of the details of suppression as a function of Δt , and will be used as the standard format in the rest of this section. In some cases, the “suppression ceiling” as defined in Chapter 3 (difference between CEOAE level in *no-suppressor* condition and noise level in *suppressor* condition) may have a bearing on the interpretation of the suppression curve, and will therefore also be plotted on the same graph. (Whenever the suppression ceiling is not plotted on such a graph, it indicates that the ceiling is outside the Y axis range.) In this particular example the suppression ceiling is at approximately 20 dB and can have no influence on the suppression curve of Figure 7.3(b).

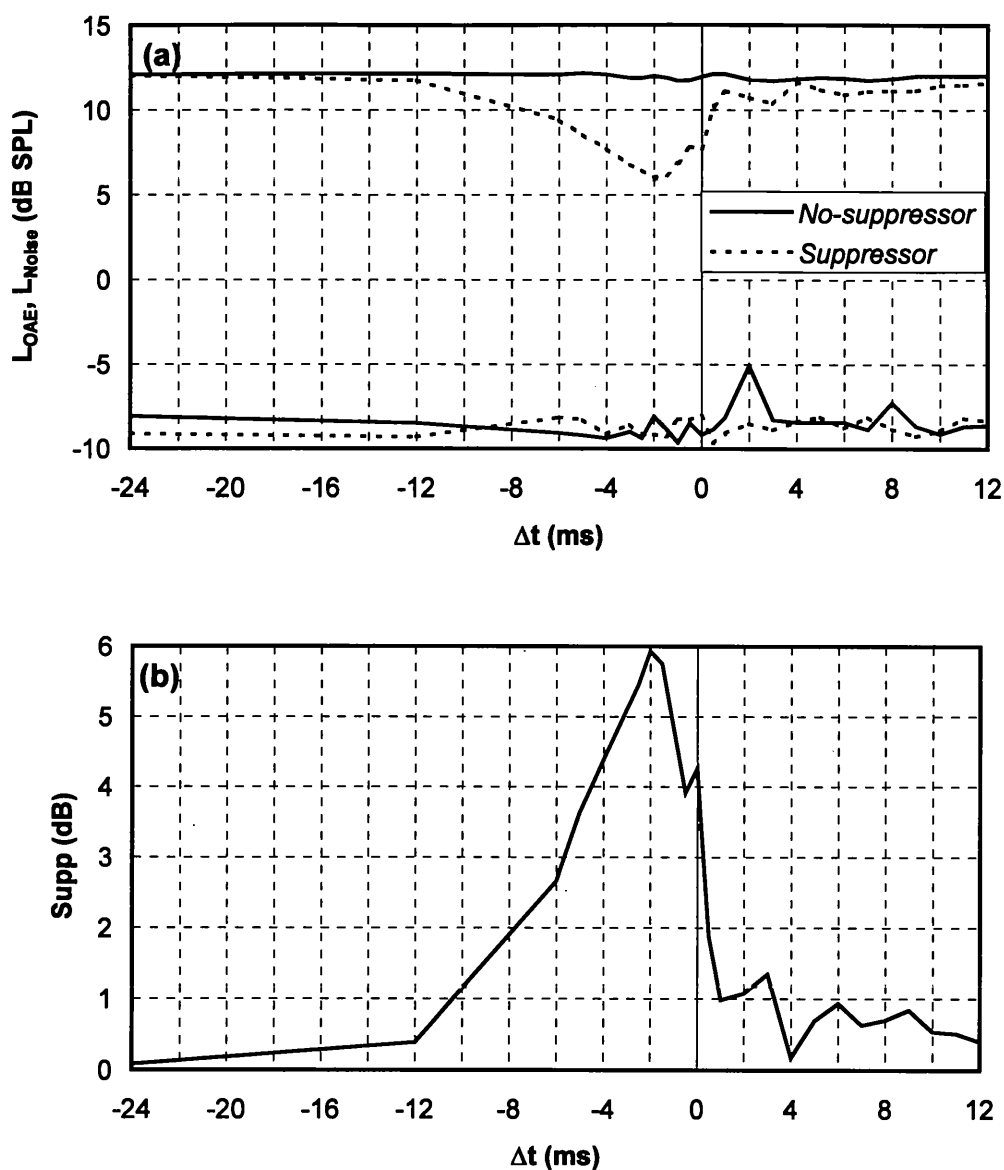


Figure 7.3. Effect of the suppressor click on the CEOAE evoked by the test click, as a function of the suppressor click delay relative to the test click (Δt). Data are for one subject and for the “whole CEOAE waveform” from 6 to 24 ms, with $L_T = L_S = 60$ dB pe SPL.

(a) The levels of the CEOAE signal (upper traces) and noise estimates (lower traces) are plotted for the no-suppressor and suppressor conditions at each value of Δt .

(b) CEOAE suppression (in dB) is plotted against Δt . This is the standard format that will be used for all such graphs in this section.

The curve of Figure 7.3(b) follows the general pattern of the curves predicted by the model of Chapter 4 (Figure 4.6), i.e. increasing suppression as the test and suppressor clicks are brought closer together. However, the measured curve here differs from that of the model in one striking respect: the peak of suppression occurs at a value of $\Delta t = -2$ ms, rather than at $\Delta t = 0$. Further, the amount of suppression at $\Delta t = 0$ (just over 4 dB) is consistent with that generated by a typical degree of CEOAE level function nonlinearity. However, the suppression value at the peak of the curve (6 dB) is not consistent with generation by level function nonlinearity, as it would entail a completely saturated level function, which is not observed in practice. As Δt increases from zero the suppression curve falls steeply, and relatively little suppression is seen at positive values. The finding that the peak in the ear canal-measured suppression curve occurred at a value of Δt less than 0 was obtained for all subjects and for almost all combinations of equilevel test and suppressor clicks (i.e. $L_T = L_S$). In some cases, the value at the peak exceeded 6 dB, which is the theoretical maximum that could be generated by (a fully saturated) level function nonlinearity.

Figure 7.4 shows the mean measured suppression (± 1 SD) at the click levels of $L_T = L_S = 60$ dB pe SPL versus Δt , across all 12 ears tested. Part of the variance in the region of Δt between 0 and -4 ms is due to the fact that although all individual curves peaked at $\Delta t < 0$, the peak positions varied slightly between individual curves. This variation in position of individual peaks also resulted in a slight reduction and broadening of the peak in the mean curve. Nevertheless, the features of the mean curve correspond very closely with those of the example curve of Figure 7.3(b).

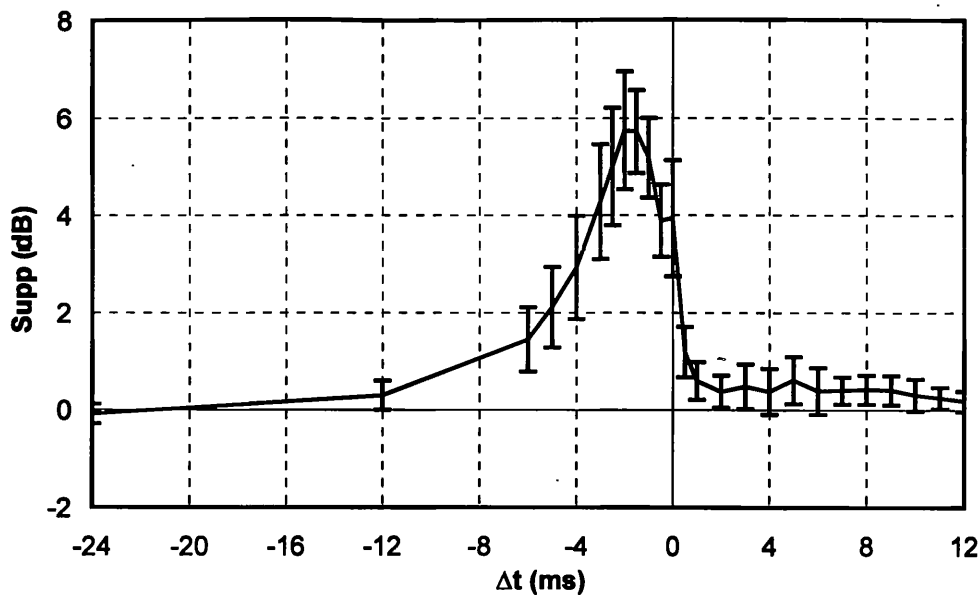


Figure 7.4. Mean measured CEOAE suppression (± 1 SD) across all 12 ears versus Δt . ($L_T = L_S = 60$ dB pe SPL.)

A second interesting feature with regard to the position of the peak of the suppression curves of the form presented above is revealed in the next figure, Figure 7.5. Here data are plotted for the same ear as in Figure 7.3, and again for $L_T = 60$ dB pe SPL but this time for all three values of L_S used in the experiment, i.e. 50, 60 and 70 dB pe SPL. In the case of $L_S = 50$ dB pe SPL, (i.e. 10 dB less than the test click level) little suppression is seen at $\Delta t = 0$, but a significant peak in the curve occurs at $\Delta t = -4$ ms. The peak then grows but also shifts towards $\Delta t = 0$ as L_S is increased relative to L_T , reaching -2 ms when L_S equals L_T (as already seen in Figure 7.3) and finally 0 ms when L_S is further increased to $(L_T + 10)$ dB. Once again this trend observed in the individual's data presented was typical of all ears tested and for all values of L_T and L_S : peaks in the curves tended to occur at Δt values well below zero for $L_S = (L_T - 10)$ dB, somewhat less than zero for $L_S = L_T$ and increasingly close to zero as L_S was made increasingly

larger than L_T . In many cases two distinct peaks were observed at intermediate values of $(L_S - L_T)$, one at $\Delta t < 0$ and one at $\Delta t = 0$.

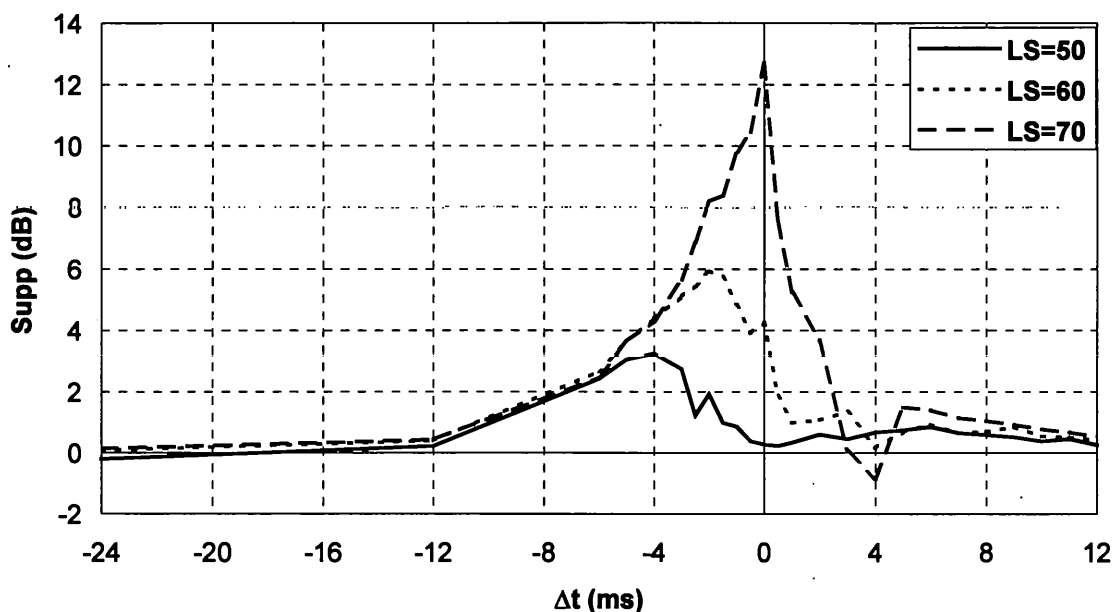


Figure 7.5. Measured CEOAE suppression versus Δt for same ear as in Figure 7.3, for $L_T = 60$ dB pe SPL and all three values of L_S .

Figure 7.6 (a) through (d) show the mean suppression versus Δt curves (thick lines) across all subjects for all test and suppressor click levels. Mean suppression ceilings are also shown (thin lines) where they lie within the Y axis ranges of the plots. Each panel in the figure shows data for a single value of L_T , and within each panel each curve represents a different value of L_S . Values of L_S are indicated relative to L_T to facilitate comparisons between panels. The general pattern of a rightward shift in peak position (from an initially negative value of Δt), as L_S is increased relative to L_T and as

suppression increases, is clearly evident in all panels. It should be noted that the apparent saturation of growth in suppression at the highest levels of L_S in panel (a) ($L_T = 40$ dB pe SPL) is not genuine, but caused by the suppression of substantial portions of many of the CEOAE waveforms into the measurement noise floors, as indicated by the proximity of the suppression ceilings. Suppression ceilings increase with L_T in line with CEOAE growth (as noise floors are largely independent of click levels). Thus, while a (minor) ceiling effect persists for the topmost curve in panel (b) ($L_T = 50$ dB pe SPL), the other curves in Figure 7.6 are largely free of such effects.

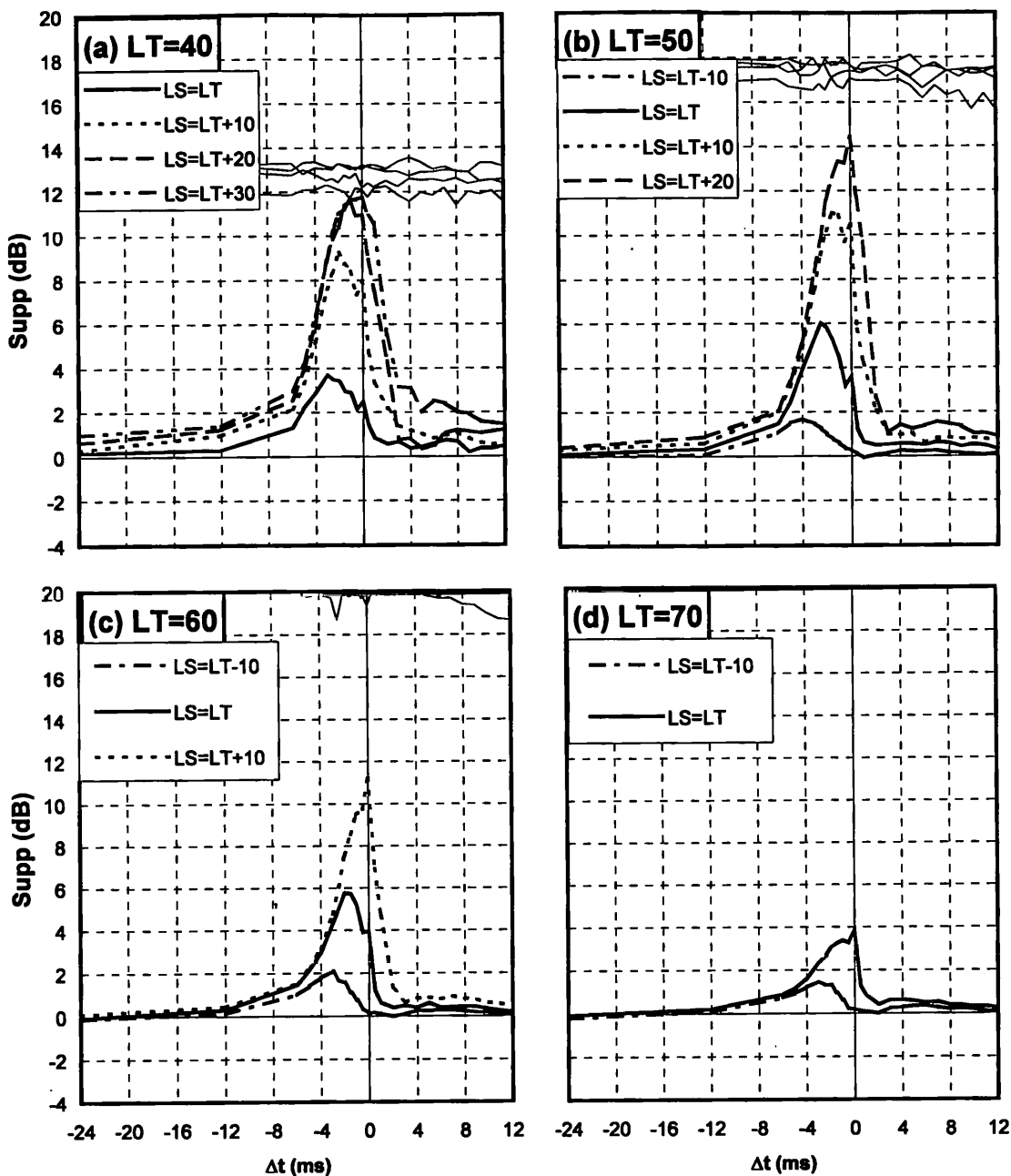


Figure 7.6 (a) through (d). Mean suppression versus Δt curves (thick lines) across all subjects for all test and suppressor click levels. Data for each of the four test click levels (L_T) are shown in a separate panel, within each of which curves are plotted for the different suppressor click levels (L_S). Suppressor levels are expressed relative to L_T to facilitate comparisons between panels. The thin lines at the tops of the panels represent the corresponding "suppression ceiling" curves, which are only shown where they may have had an influence on the suppression values measured. (Where suppression ceilings are not shown, they are above the Y axis range and could not have influenced the suppression measures.) As suppression ceilings are largely independent of L_S , they are not separately identified within each panel. (Data are for the "whole CEOAE waveforms", i.e. 6-24 ms segments.)

A small increase in amplitude of the CEOAE (negative value of suppression) can be seen in the data for the individual ear presented in Figure 7.5, for $L_S = 70$ dB pe SPL at $\Delta t = +4$ ms. Such enhancements of the CEOAE amplitude due to the presentation of a following suppressor click were occasionally observed at isolated (positive only) values of Δt , usually for $L_S > L_T$. These actually represented an increase in amplitude in a highly localised region of the waveform, usually accompanied by a change in the pattern of the waveform in that region. Such waveform changes are evident at $\Delta t = 4$ ms in the 10-13 ms segment of the example waveforms (from the same individual ear) presented earlier in Figure 7.1. As these enhancements occurred only occasionally, and for different parameter conditions and different waveform locations between subjects, they are not evident in the mean curves of Figure 7.6. Furthermore, the “whole waveform” measures of CEOAE amplitude significantly underestimate the magnitude of these local enhancements. The whole waveform measures also underestimate the magnitude of suppression due to following suppressors, as the suppressive effects are limited to increasingly later portions of the CEOAE waveform. The degree of underestimation is compounded by the characteristic of CEOAEs that the later waveform segments tend to have progressively smaller amplitudes, and are thus under-represented in the whole waveform measures.

An accurate representation of the effects of following suppressors on the CEOAE therefore requires that suppression be measured in smaller time segments than the whole waveform segment from 6 to 24 ms. Such representations of the suppression phenomenon also allow a comparison of the suppressibility of different segments of the waveform, for both leading and following suppressors.

7.3.2 Waveform segment measures

Figure 7.7 through to Figure 7.14 show plots of suppression versus Δt in the same format as the whole CEOAE waveform plots of Figure 7.6, but now for eight successive 3-ms time segments that span the entire recorded waveforms from 0 to 24 ms.

As discussed in Chapter 3, the section of the recording between 0 and 6 ms was not normally included in the CEOAE waveform for analysis purposes. This section is included in the following figures for completeness, and for the sake of the following brief discussion. All eight figures use a common Y axis range in order to facilitate comparisons between them, except for Figure 7.7, in which a highly expanded Y axis range is used.

Figure 7.7 shows that no suppression is measured in the 0-3 ms waveform segment for any combination of values of L_T , L_S and Δt (the maximum suppression value in all of the data shown here is 0.1 dB). This is consistent with the fact that the 0-3 ms segment is overwhelmingly composed of the (linear) click stimulus itself, rather than the CEOAE response. The data further confirm that suppression as measured here is a property of nonlinearly interacting signals and that the experimental set-up generates no such nonlinearities at any of the click levels used in the experiment.

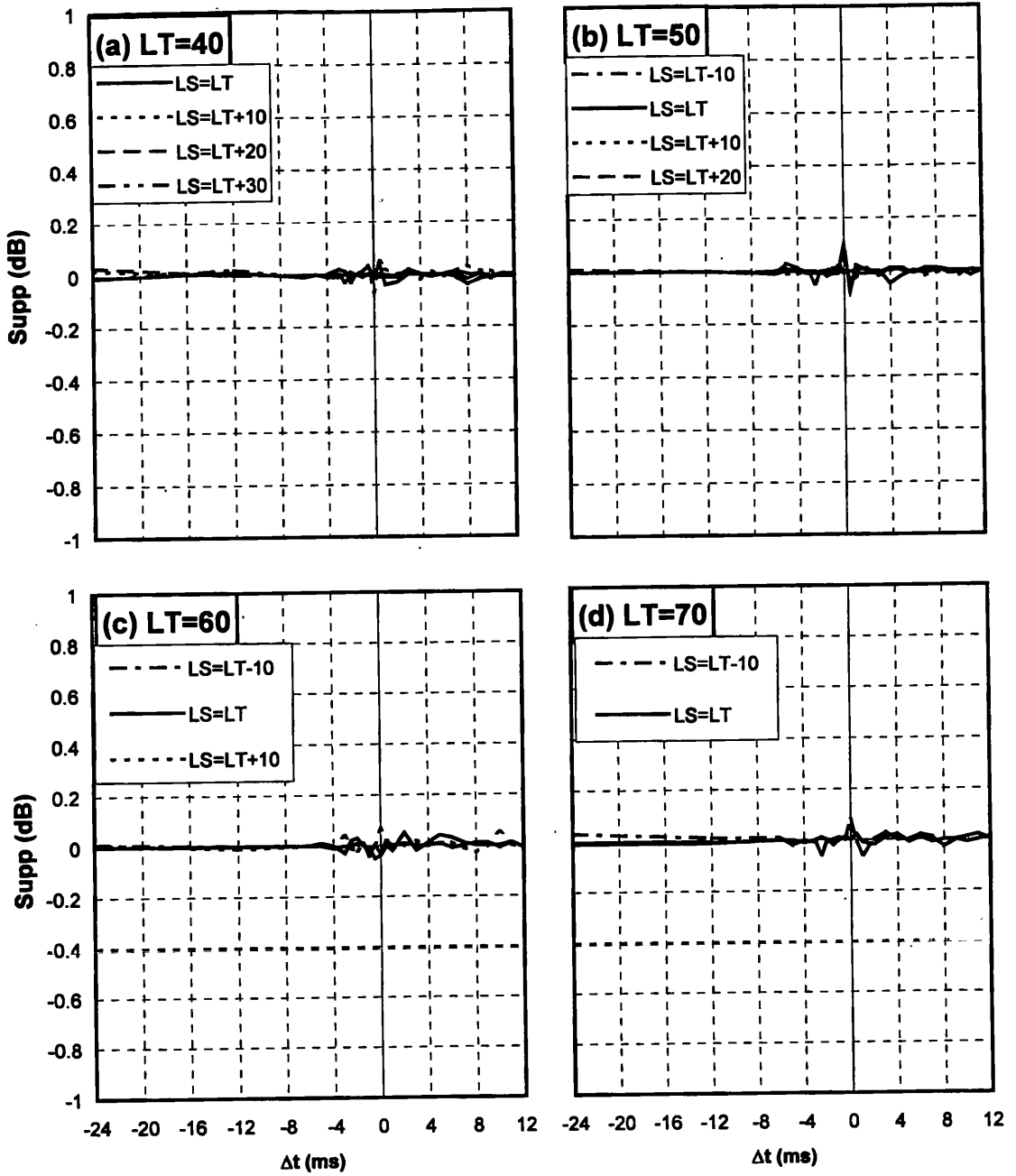


Figure 7.7 (a) through (d). Mean suppression versus Δt curves for 0-3 ms waveform segment. Format of figure follows Figure 7.6.

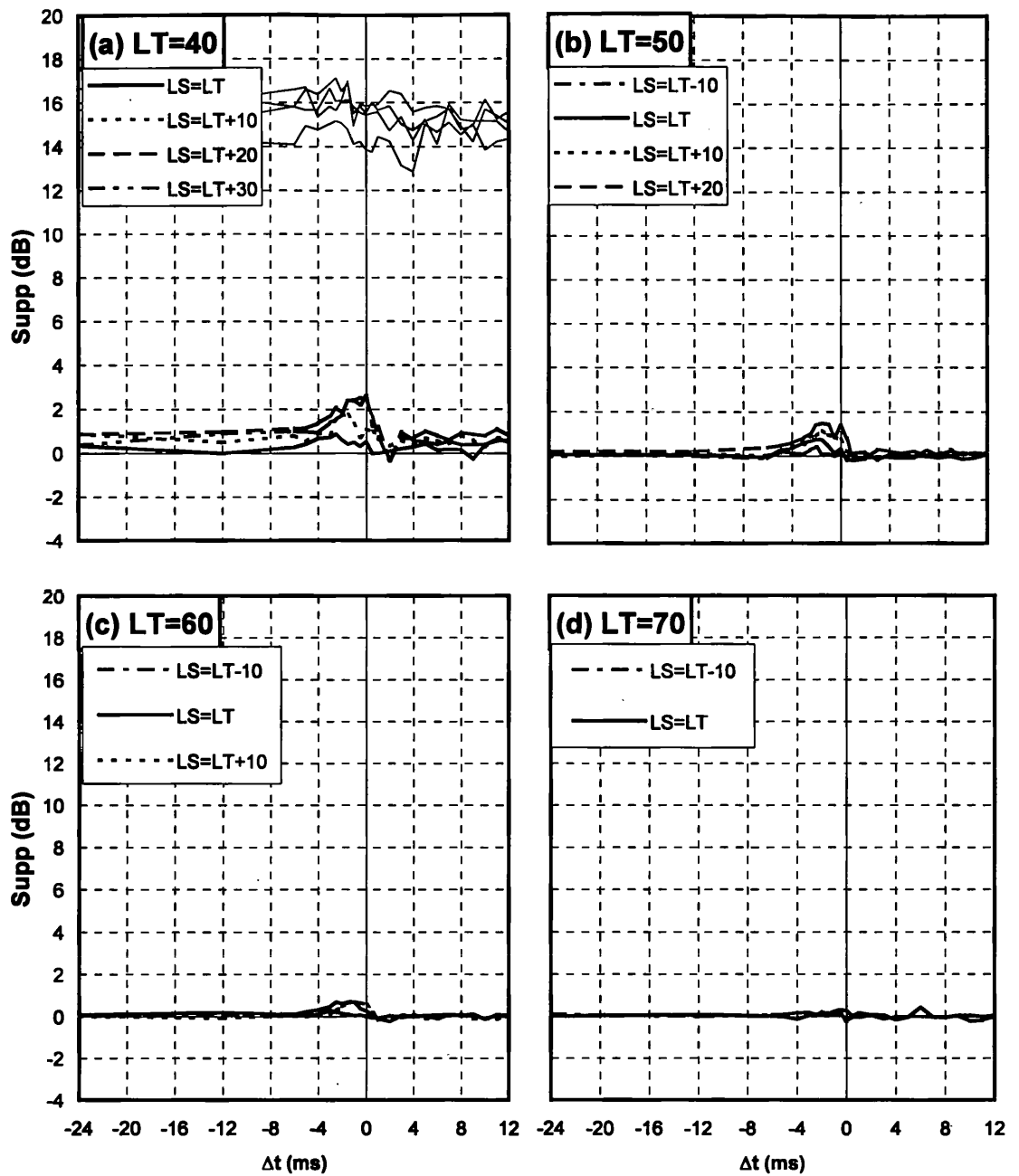


Figure 7.8 (a) through (d). Mean suppression versus Δt curves for 3-6 ms waveform segment. Format of figure follows Figure 7.6.

Figure 7.8 shows the corresponding suppression data for the 3-6 ms waveform segment. These plots show a small amount of suppression (less than 3 dB) at the lowest level of the test click ($L_T = 40$ dB pe SPL), progressively reducing with increasing L_T , with no suppression evident at $L_T = 70$ dB pe SPL. The data are consistent with the expectation that the 3-6 ms segment contains a mixture of the (non-cochlear) “ringing” response of the click and the early portion of the CEOAE, with an increasing proportion of the ringing as L_T is increased. As the (linear) ringing is expected to dominate this waveform segment at the test click level of 70 dB pe SPL, no suppression is seen in panel (d). Once again, the data confirm that the experimental set-up generates no relevant nonlinearities over the range of measurement parameters.

Figure 7.9 through to Figure 7.14 (representing successive 3-ms segments within the 6 to 24 ms extent of the waveforms) are highly similar to the whole CEOAE waveform plots of Figure 7.6, for Δt values ≤ 0 . Data within all these segments show the key feature of the whole waveform curves, of the peak in suppression occurring at Δt values well below zero for the lower values of L_S (relative to L_T) but a shift of the peak towards $\Delta t = 0$ as L_S increases relative to L_T . However, the later waveform segments (Figure 7.12 through Figure 7.14), being of lower baseline amplitudes, are also associated with progressively lower suppression ceilings, which has the effect of obscuring the peak positions (as well as peak values) at the higher values of L_S .

As expected, however, for $\Delta t > 0$ (following suppressors) the plots in 3-ms segments reveal aspects of the suppression that are not evident in the whole waveform data. In general, considerably more suppression is evident for following suppressors in these plots than in the whole-waveform plots. The later waveform segments also tend to

show more suppression than the earlier ones, even for Δt values that are only slightly greater than zero. (See e.g. the successive figures for $L_T = 70$ and $\Delta t = 4\text{ms}$.) Indeed, for the later segments, and for the lower values of L_S relative to L_T , the amount of suppression due to following suppressors can equal or even exceed that due to leading or synchronous suppressors (see Figure 7.13 and Figure 7.14). This suppression due to following suppressors is, however, much less sensitive to increases in L_S than that due to leading or synchronous suppressors. As a result, the latter dominates at high values of L_S relative to L_T (except where it is limited by the suppression ceilings).

When examined in the 3-ms segment plots, suppression due to following suppressors also varies far less smoothly as a function of Δt than does suppression for leading suppressors. This tendency in the mean curves presented here also applied to the corresponding curves for each individual subject.

A third feature evident in the mean curves for data within 3-ms segments, but not in the whole-waveform plots, is the occasional enhancement (negative value of suppression) seen for positive values of Δt and for $L_S > L_T$, as in the example of individual data presented in Figure 7.5. These enhancements are often seen in the curves for $L_S = L_T + 10$ and particularly for $L_S = L_T + 20$, but *not* for $L_S = L_T + 30$. Where enhancements occur, they are clustered around Δt values of +2 to +6 ms. Furthermore, while enhancements are seen (at some click levels) for all the 3-ms segments between 6 and 18 ms, they are never seen for the very late segments, i.e. 18-21 and 21-24 ms.

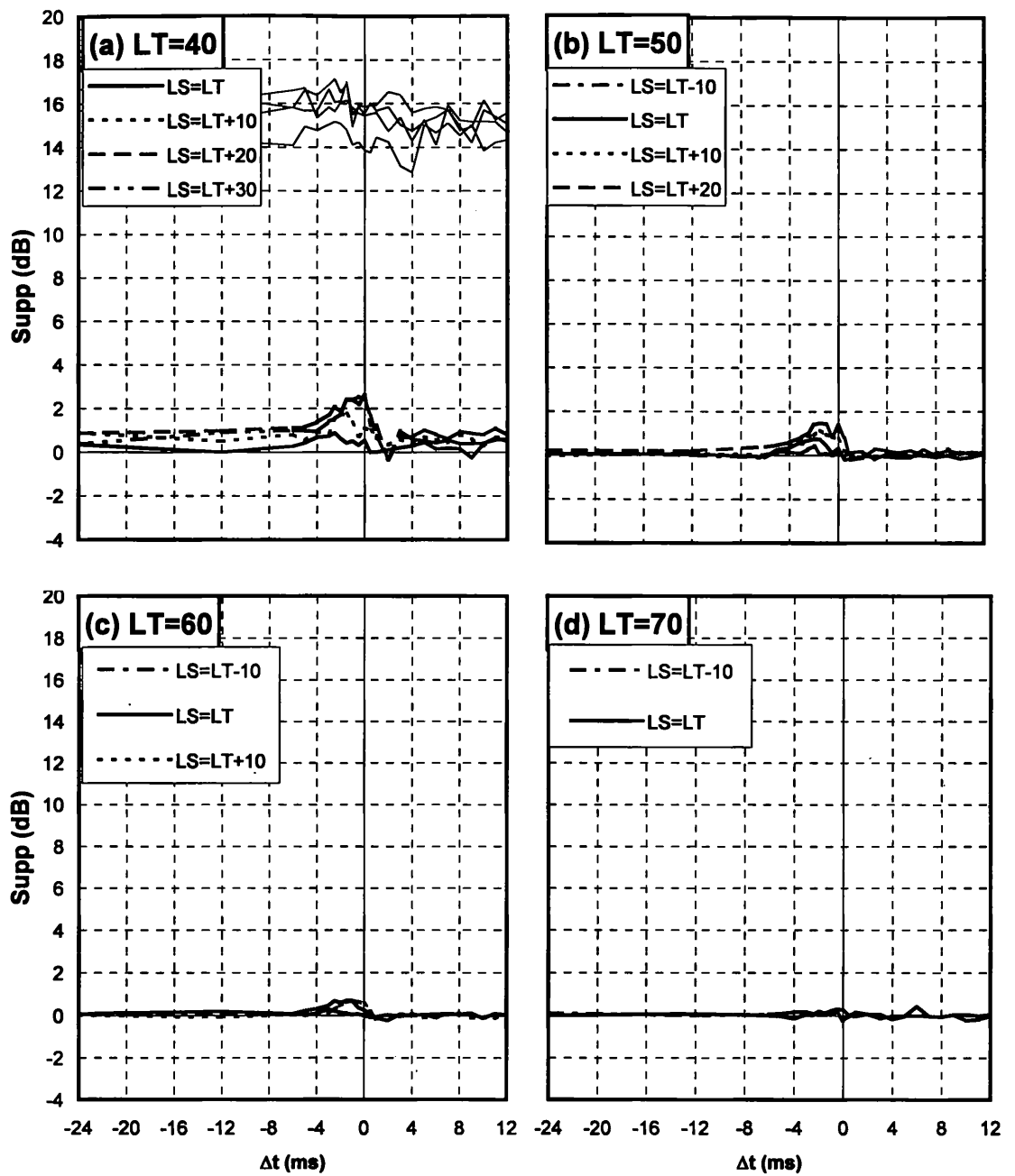


Figure 7.9 (a) through (d). Mean suppression versus Δt curves for 6-9 ms waveform segment. Format of figure follows Figure 7.6.

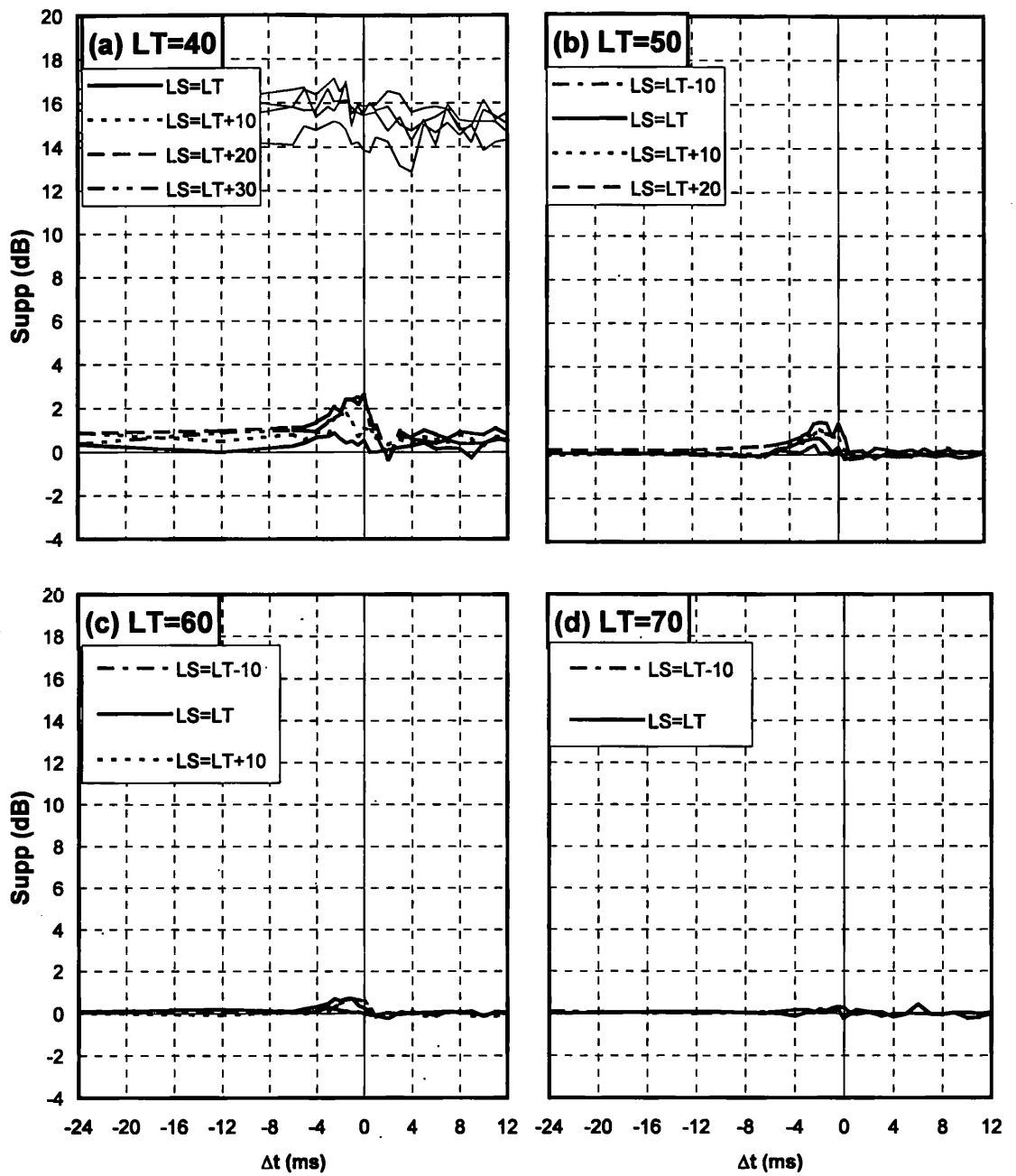


Figure 7.10 (a) through (d). Mean suppression versus Δt curves for 9-12 ms waveform segment. Format of figure follows Figure 7.6.

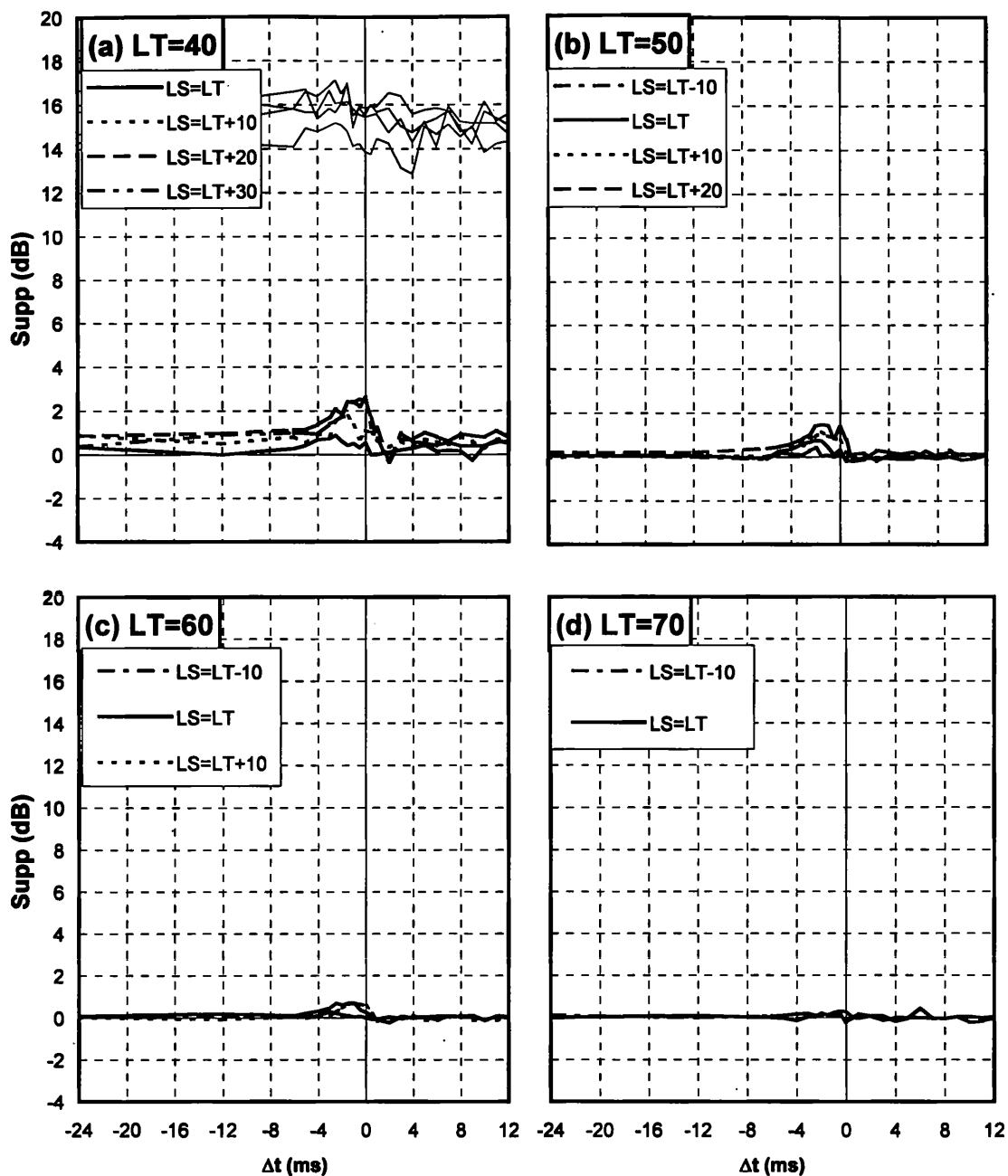


Figure 7.11 (a) through (d). Mean suppression versus Δt curves for 12-15 ms waveform segment. Format of figure follows Figure 7.6.

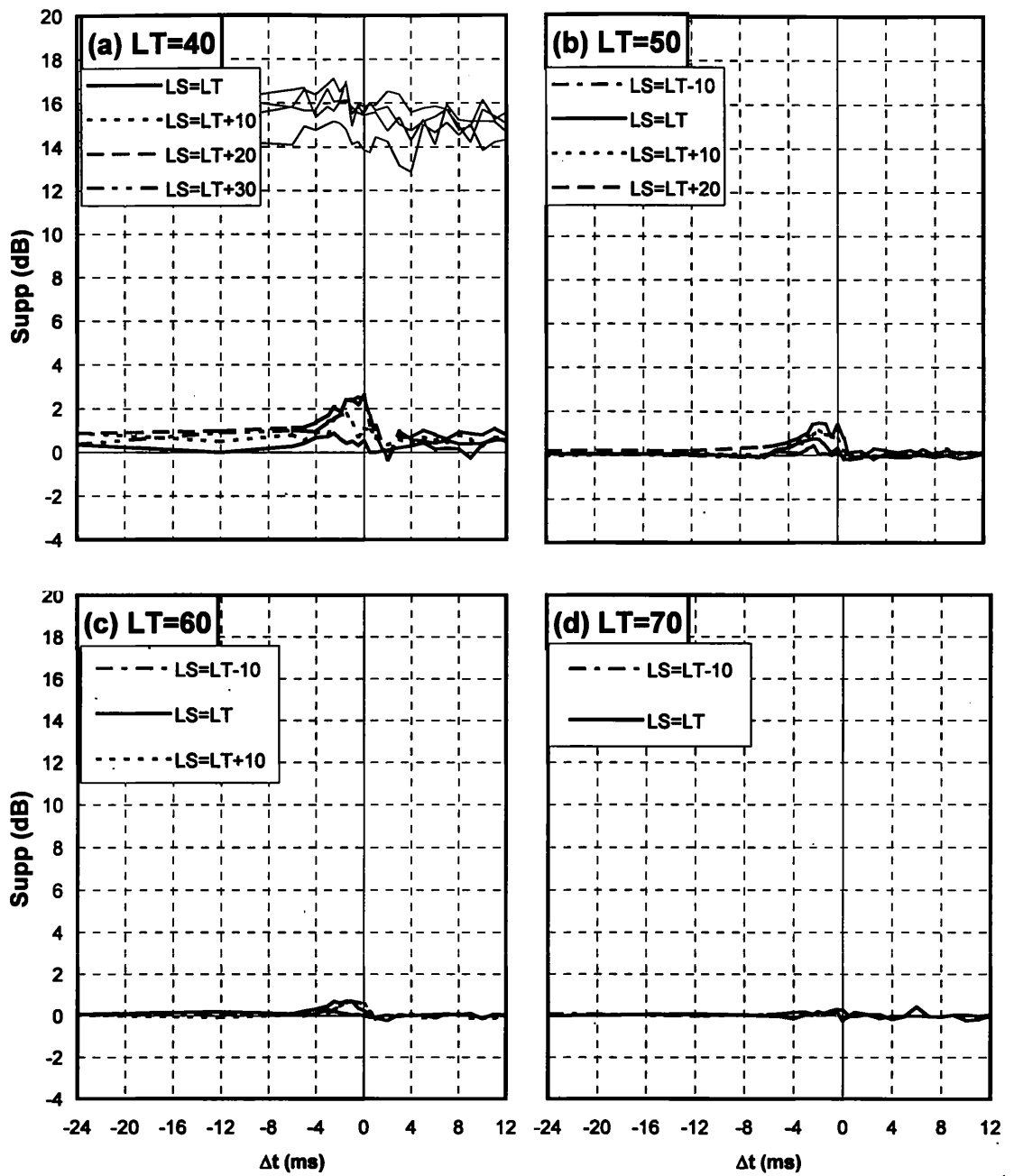


Figure 7.12 (a) through (d). Mean suppression versus Δt curves for 15-18 ms waveform segment. Format of figure follows Figure 7.6.

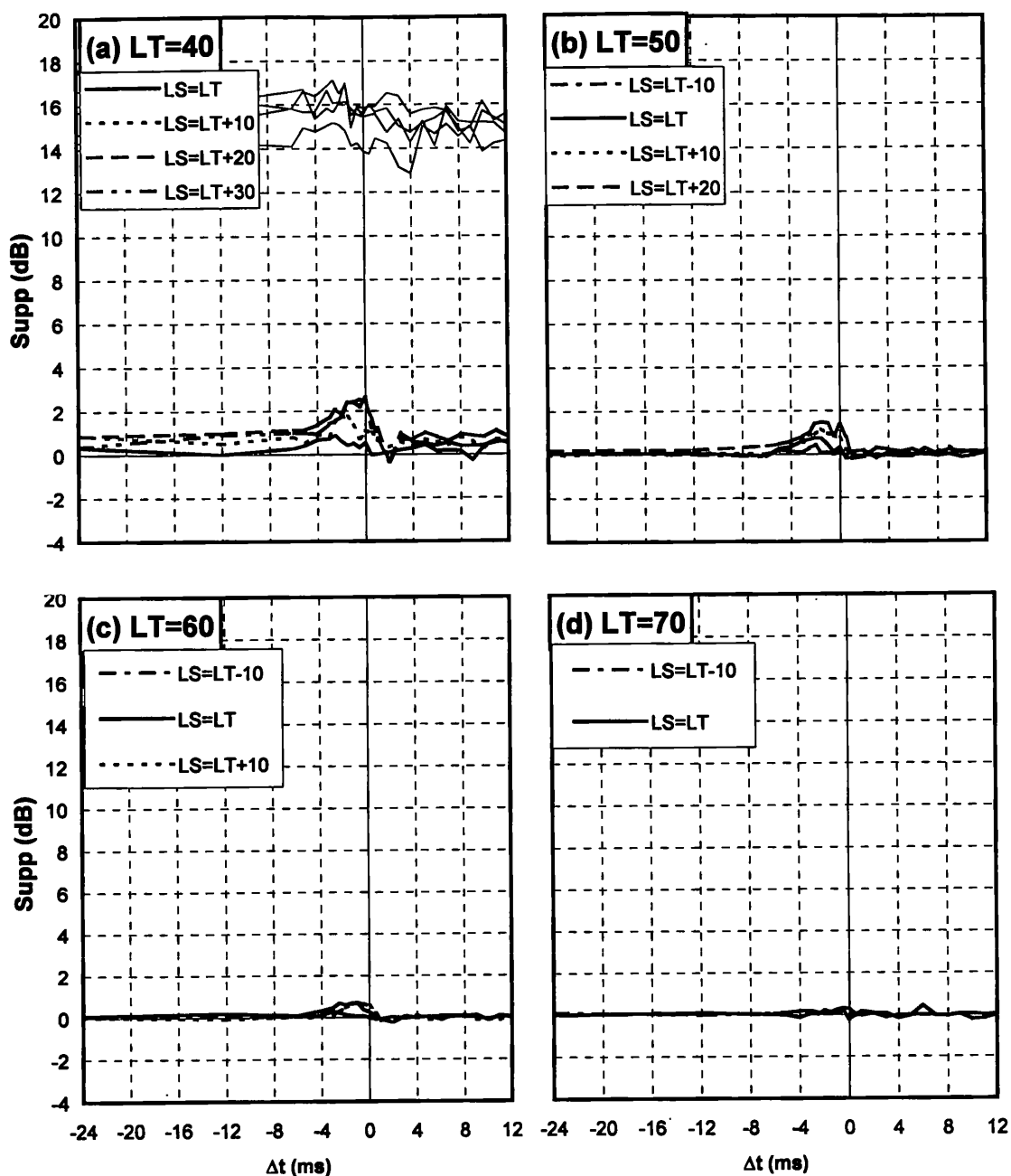


Figure 7.13 (a) through (d). Mean suppression versus Δt curves for 18-21 ms waveform segment. Format of figure follows Figure 7.6.

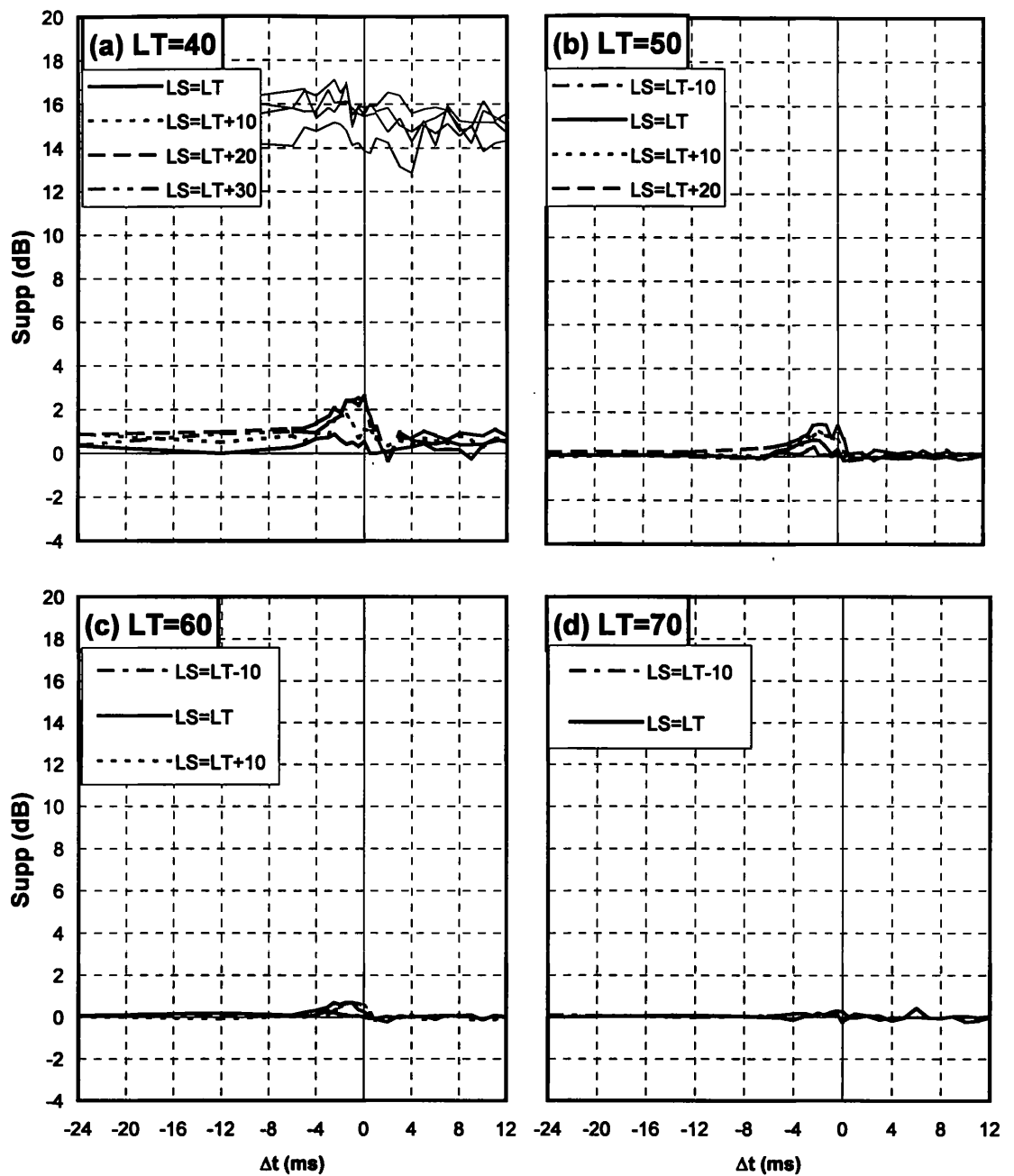


Figure 7.14 (a) through (d). Mean suppression versus Δt curves for 21-24 ms waveform segment. Format of figure follows Figure 7.6.

The data presented in this section (Section 7.3) represent the general form of the results for the whole CEOAE waveforms and for the waveforms divided into 3 ms segments. The following sections present a more detailed examination of various aspects of these general results.

7.4 Influence of L_S-L_T on suppression maxima

Within any one waveform segment, the curves of suppression versus Δt show the same key features as the whole-waveform curves, with respect to the dominant peaks (suppression maxima) of the curves at $\Delta t \leq 0$. The dependence of the position of these suppression maxima upon the value of L_S (relative to L_T) is more clearly depicted in Figure 7.15. To generate this figure, an analysis of the individual curves for each subject was first performed, in order to identify the value of Δt that corresponded to the peak of the curve for each condition of L_T and L_S . These values of Δt (denoted Δt_{pk}) were then plotted versus L_S-L_T , separately for each value of L_T . (As the 3 ms segment curves follow the same pattern as the whole-waveform curves, data are plotted only for the latter in this figure). Data for the single condition of $L_S-L_T = 30$ dB ($L_T = 40$, $L_S = 70$ dB pe SPL) are not included in this analysis, due to the limiting effects of the suppression ceilings in this condition (see Figure 7.6).

Linear regression trend lines (dashed lines) for each L_T condition confirm the tendency for Δt_{pk} to change from negative values towards zero as L_S-L_T increases. (Individual Δt_{pk} values can be seen to converge on zero rather than uniformly increase – only a single positive value of 0.5 ms was observed, which is likely to have been a chance

observation due to experimental error.) This tendency is also stronger (increasing slopes of the trend lines) for higher values of L_T . Note that the flattening of the curve in panel (b) is partly due to the convergence of Δt_{pk} values to zero. (The analysis was performed without smoothing the individual suppression curves, which may have reduced the variability due to random error but may also have obscured trends with respect to peak position.) The Spearman correlation coefficient obtained separately for each curve confirms a highly significant correlation ($p < 0.001$) in each case.

A similar analysis of the dependence of the heights of the peaks of individual suppression curves upon $L_S - L_T$ is shown in Figure 7.16. The figure shows a strong and near “linear” (for both variables expressed in dB) positive relationship between peak heights and $L_S - L_T$. In this case, the flattening of the curves in panels (a) and (b) can be attributed to the limiting effects on peak heights of the suppression ceilings at these levels, as shown and discussed in Figure 7.6. The slope of the curve is somewhat less in panel (d) than in the other three panels, indicating a lesser influence of $L_S - L_T$ on peak height at the highest value of L_T of 70 dB pe SPL. Once again, the Spearman coefficient confirms a highly significant correlation ($p < 0.001$) for the data in each panel.

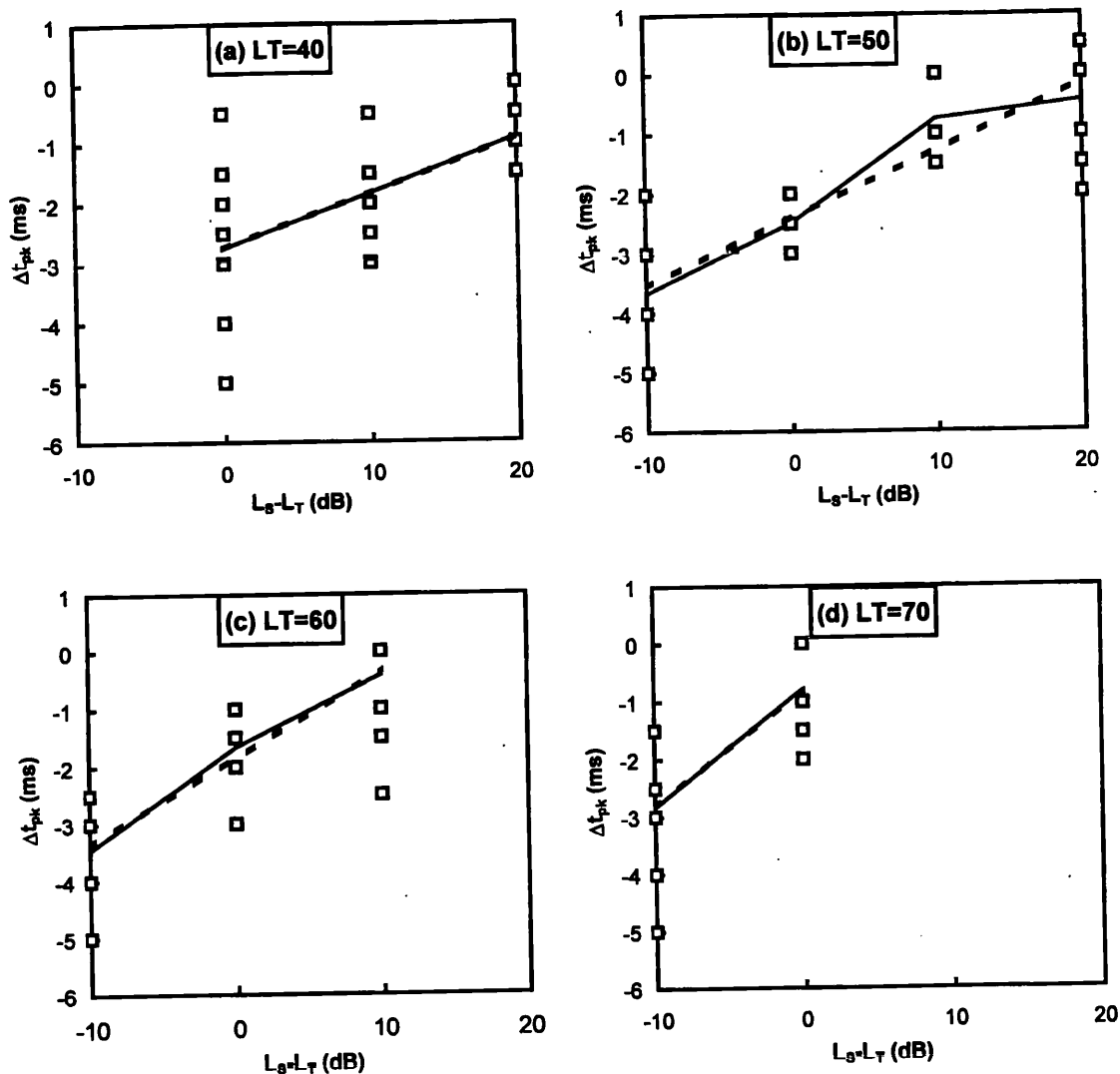


Figure 7.15. Dependence of position of dominant peaks of individual suppression curves (Δt_{pk}) on the level of L_S relative to L_T . Note that there are 12 data points (representing the 12 subjects) at each plotted abscissa value - mean values are connected by solid lines. Linear-fit trend lines are also included in each panel (thick dashed lines). Data are for the whole CEOAE waveforms, and exclude the single condition of $L_S - L_T = 30$ dB.

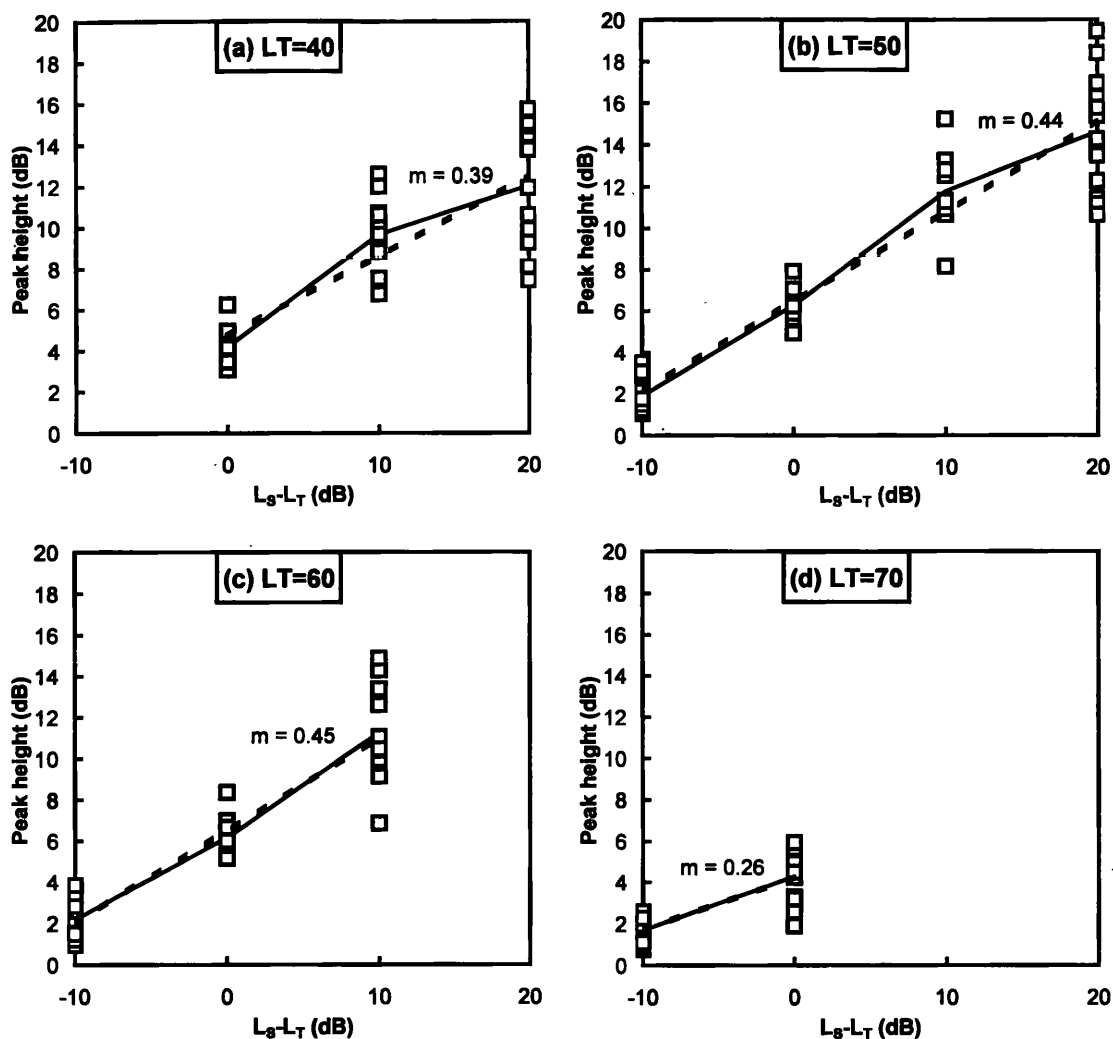


Figure 7.16. Dependence of height of the peaks of individual suppression curves on the level of L_S relative to L_T . The format of the figure is similar to that of Figure 7.15, with solid lines indicating mean values and thick dashed lines linear-fit trendlines (slopes labelled).

7.5 Influence of waveform time segment on suppression patterns

The relationship between the suppression patterns *across* waveform segments can be better observed by plotting the curves of Figure 7.7 through Figure 7.14 for *fixed* values of L_S and L_T , and with the waveform segment as a parameter. Graphs of this form are shown in Figure 7.17 through Figure 7.20 (the 0-3 and 3-6 ms segments of the waveform are not included here). As previously noted, the figures show that all waveform segments exhibit a similar pattern with respect to the position of the dominant peak of the curve, and its dependence on the value of L_S relative to L_T . Furthermore, for given values of L_T and L_S (within each panel), the dominant peak (at $\Delta t \leq 0$) occurs at broadly the same position for all the waveform segments, i.e. there are no systematic differences in peak position between early and late waveform segments. Similarly, there are no major differences in peak height (maximum suppression) between early and late waveform segments. (Although there is a slight tendency for lower peak heights among the later waveform segments, this is accompanied by progressively lower suppression ceilings, which increasingly limit the suppression values measured.)

In marked contrast, for following suppressors, a striking trend for an increasing degree of suppression in the progressively later waveform segments is evident. For the very late waveform segments, and when L_S is less than L_T (panel (a) in each of Figure 7.18 through Figure 7.20), suppression due to suppressors that follow the test click by between 4 and 12 ms can equal or exceed suppression due to suppressors at $\Delta t \leq 0$. This dominance of the effects of the following suppressors in the very late waveform segments also applies when $L_S = L_T$ for the higher values of L_T (panel (b) in each of Figure 7.19 and Figure 7.20).

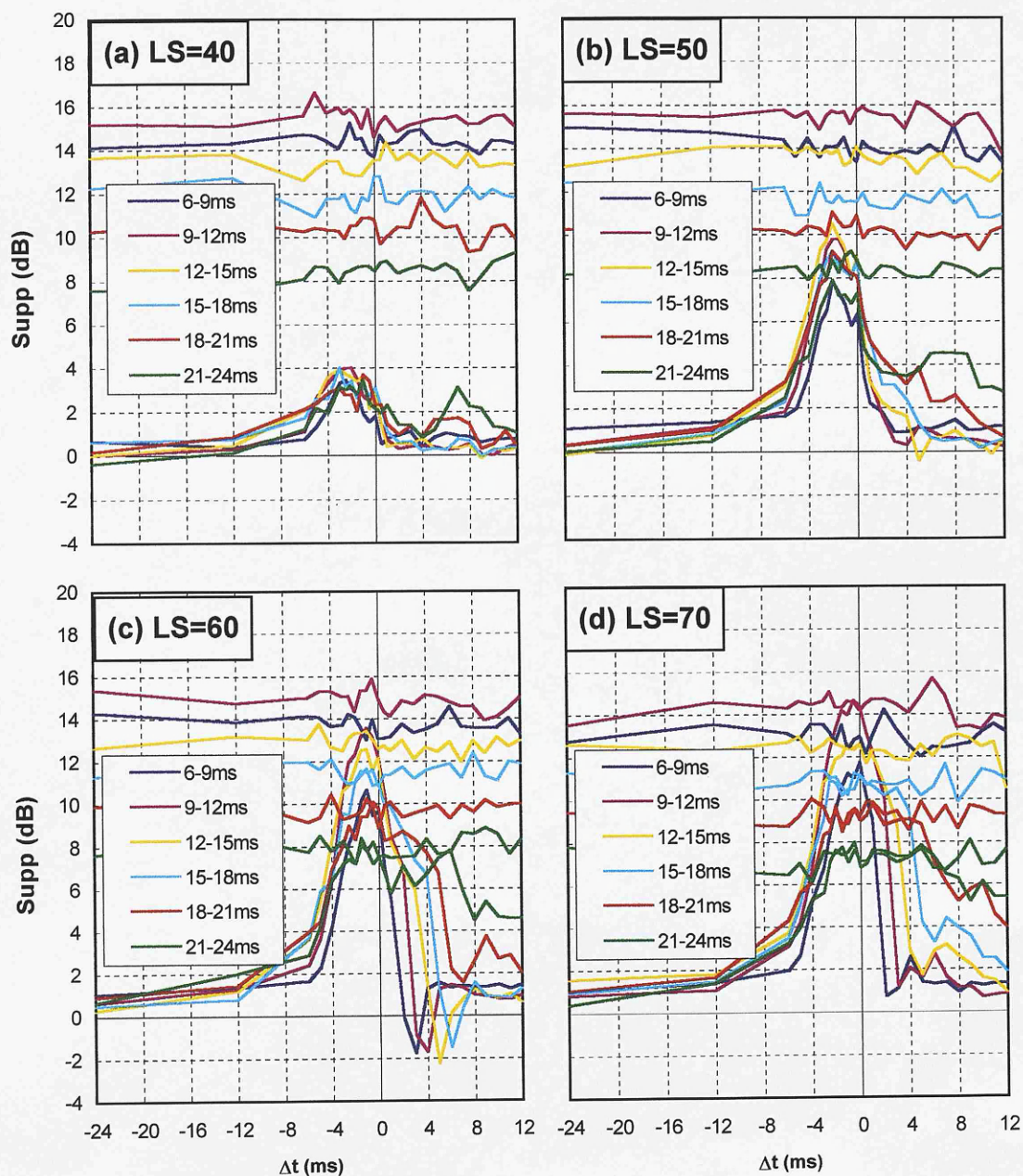


Figure 7.17 (a) through (d). Mean suppression versus Δt curves by waveform segment. Data are shown for $L_T=40$ dB pe SPL, and separately in each panel, for each value of L_S . The suppression ceiling for each segment is also shown.

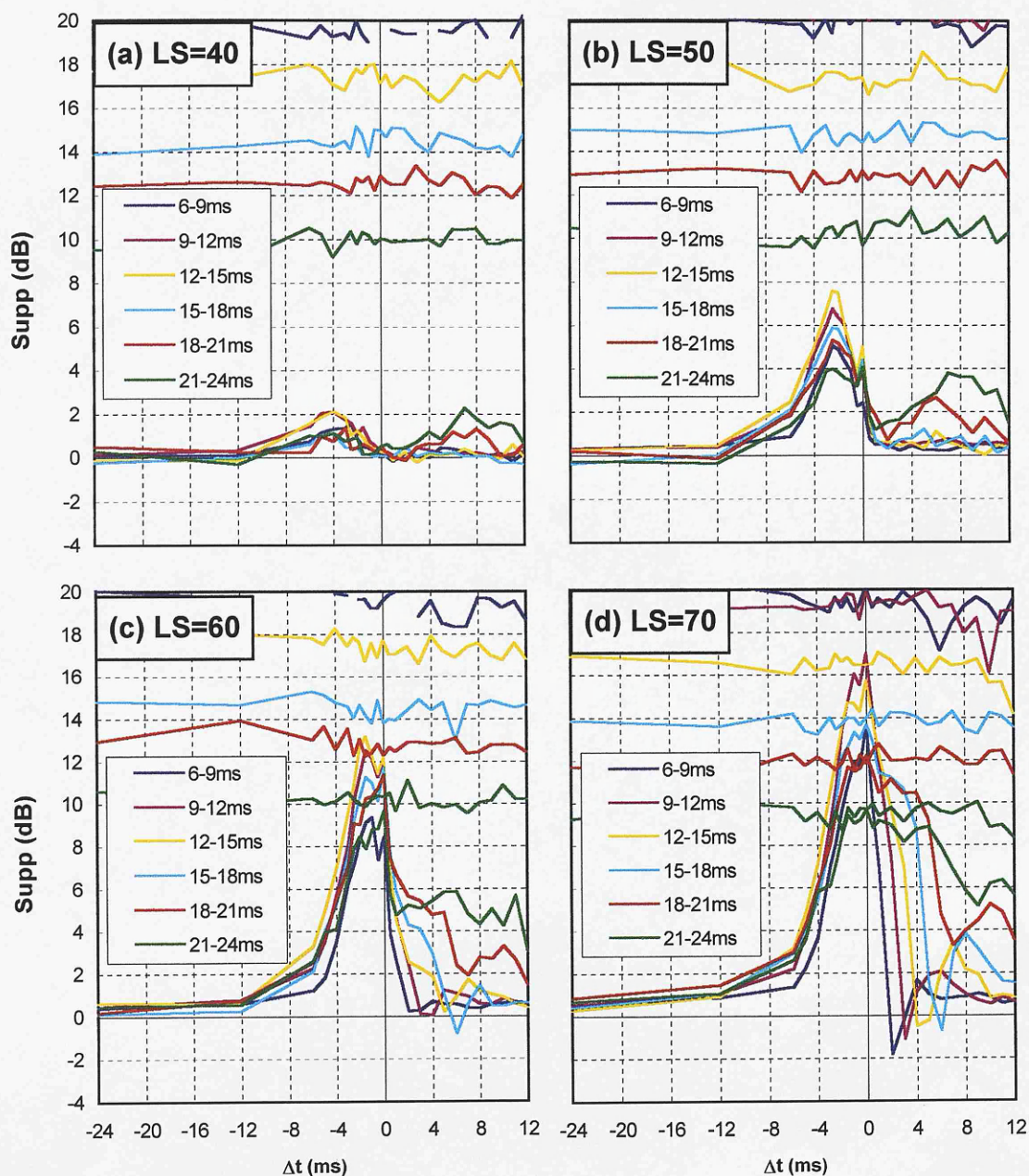


Figure 7.18 (a) through (d). Mean suppression versus Δt curves by waveform segment. Data are shown for $L_T=50$ dB pe SPL, and separately in each panel, for each value of L_S . The suppression ceiling for each segment is also shown.

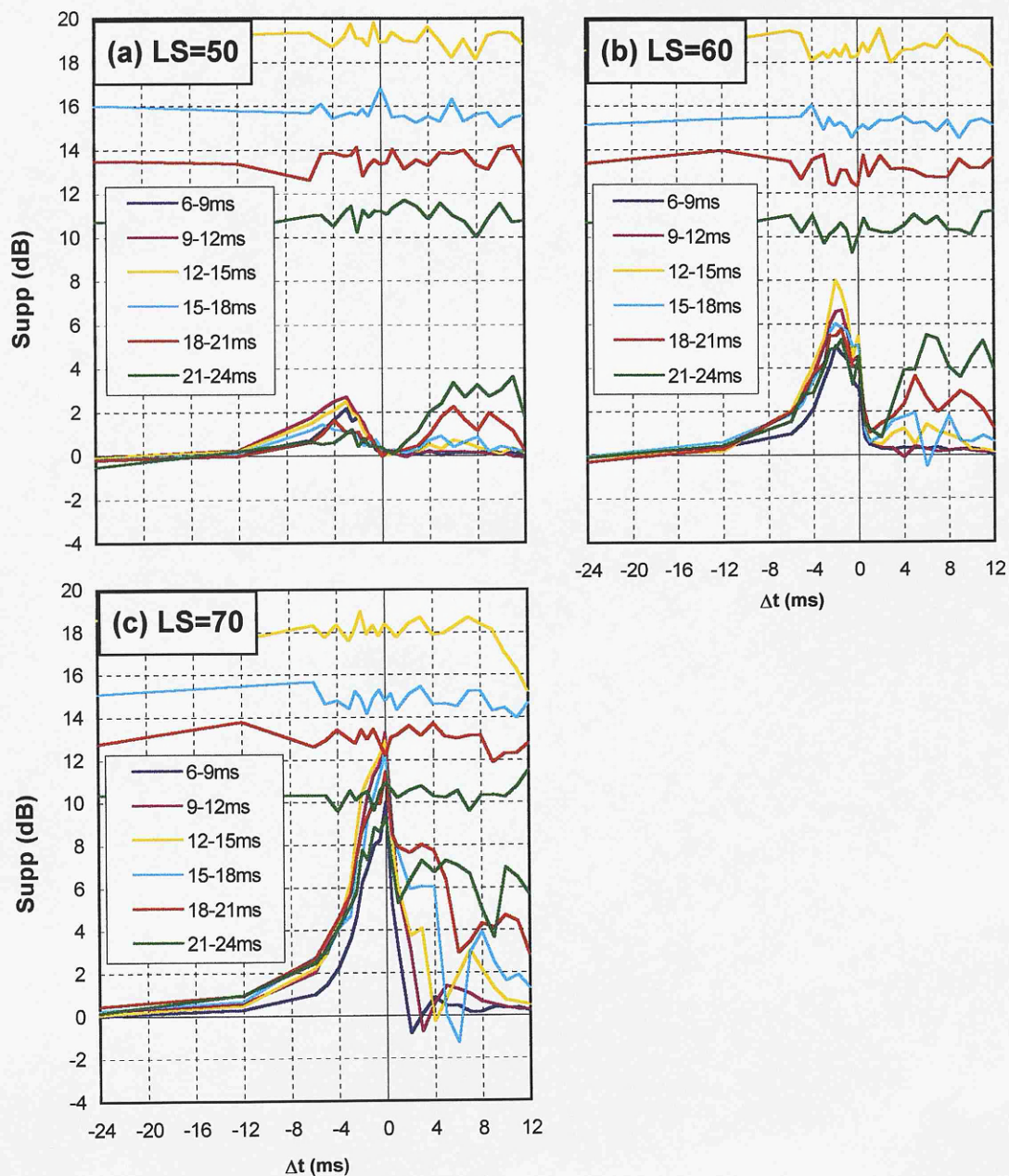


Figure 7.19 (a) through (c). Mean suppression versus Δt curves by waveform segment. Data are shown for $L_T=60$ dB pe SPL, and separately in each panel, for each value of L_S . The suppression ceiling for each segment is also shown.

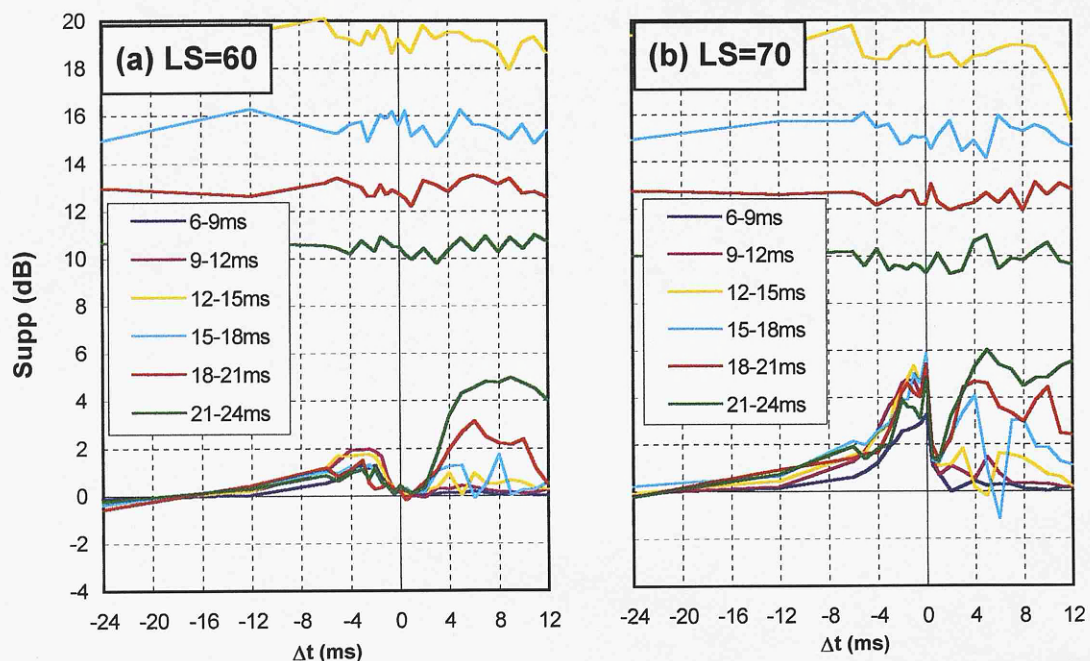


Figure 7.20 (a) and (b). Mean suppression versus Δt curves by waveform segment. Data are shown for $L_T=70$ dB pe SPL, and separately in each panel, for each value of L_S . The suppression ceiling for each segment is also shown.

Figure 7.21 highlights the systematic dependence of suppression for following suppressors upon waveform segment. From the data of Figure 7.17 through Figure 7.20 a single value is obtained for such suppression, as the mean suppression value for all Δt values between +1 and +12 ms inclusive. This mean suppression value for $\Delta t > 0$ within each 3 ms segment is plotted against the start point of each time segment. Data are plotted in separate panels for each value of L_T , and as separate curves for each value of L_S . All the curves show the trend of suppression increasing with segment start time in a near-monotonic fashion. Note that the apparent down-turn in the curve for $L_S = 70$ at a segment start of 21 ms in panel (a) is spurious, and due to the effect of the suppression ceiling for this segment (see also Figure 7.17 (d)).

Figure 7.17 through Figure 7.20 also show a dependence upon values of L_T in relation to the occurrence of CEOAE *enhancements* (negative suppression) due to following suppressors. Thus, while for the lower two values of L_T , these enhancements occur predominantly when L_S exceeds L_T by 20 dB (Figure 7.17(c), Figure 7.18(d)); for $L_T = 60$ dB pe SPL, a similar pattern of enhancements occurs for $L_S = L_T + 10$ dB (Figure 7.19(c)). In addition, referring to the above three panels, a distinct sequence in the positions of enhancement maxima (troughs) in the curves for successive waveform segments can be seen. These enhancement maxima occur at successively larger values of Δt , between 2 and 6 ms, for the successive waveform segments between 6 and 18 ms. For $L_T = 70$ dB pe SPL, a single instance of enhancement is seen (Figure 7.20(b)), this time for $L_S = L_T$.

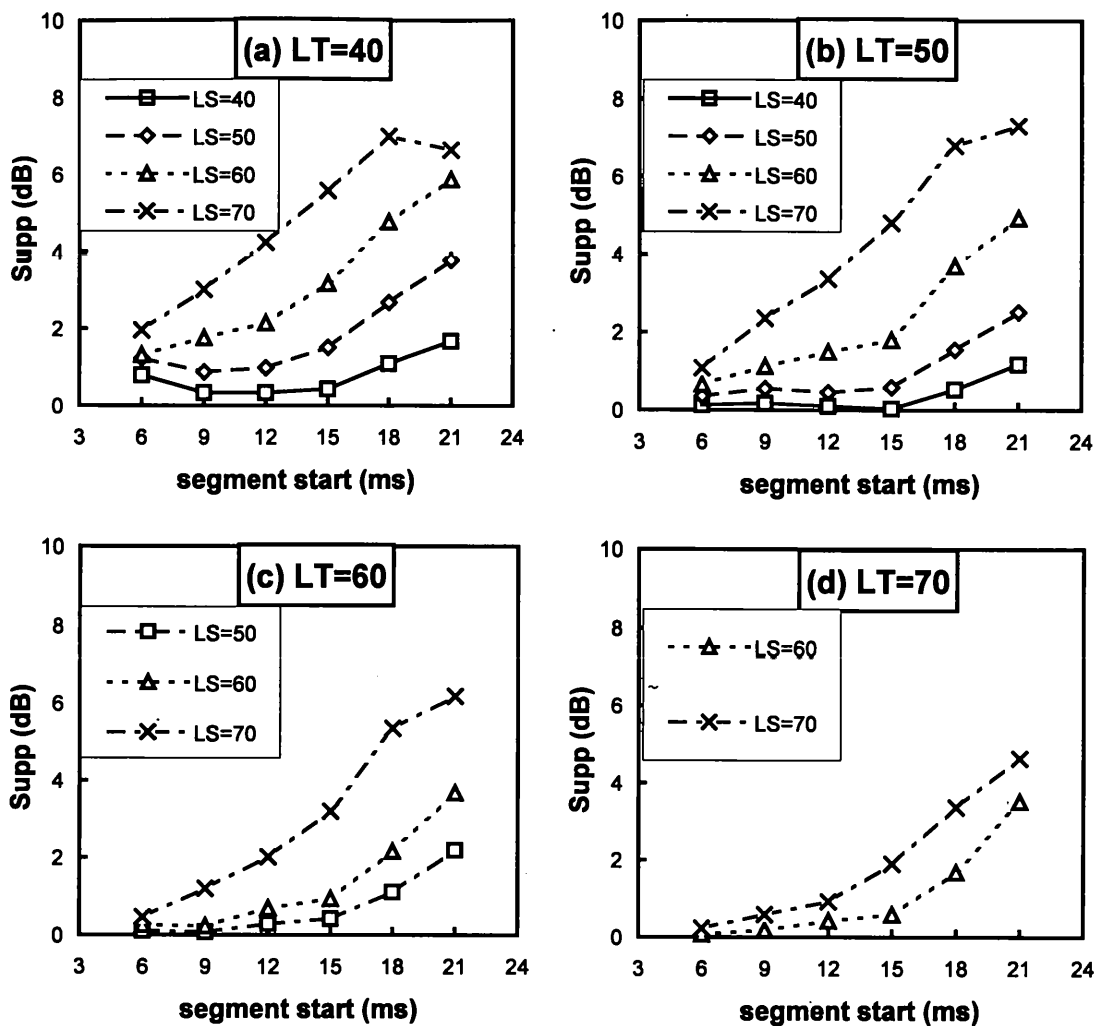


Figure 7.21 (a) through (d). Mean suppression for all following suppressors (positive values of Δt) within each 3 ms segment versus segment start time.

7.6 Dependence of suppression patterns on levels of both clicks

The dependence of suppression patterns on the levels of *both* clicks is most easily seen in Figure 7.22. Here the mean suppression curves for the whole CEOAE waveform are shown grouped into panels by the value of L_S relative to L_T . Within each panel, successive curves show the effects of equal increases in both the click levels. (Note that as these data only included a single curve for the condition of $L_S = L_T + 30$, i.e. $L_T = 40$ and $L_S = 70$ dB pe SPL, it is not plotted in this figure.) Comparing the curves across panels, the dominant feature of the peaks of the curves shifting from negative values of Δt towards $\Delta t = 0$ while L_S increases relative to L_T is evident. However, the same effect is also seen *within* each panel as the levels of both L_S and L_T are increased together. Although the shifts in peak position are smaller here, they are consistent across all four panels.

Scatter plots and regression lines relating peak positions (Δt_{pk}) to L_T , for fixed values of $L_S - L_T$, are shown in Figure 7.23. The figure follows the format of Figure 7.15, except that in this case the abscissa represents the level of the test click (L_T) and $L_S - L_T$ is fixed within each panel. (Note that there is no panel for $L_S - L_T = 30$ dB, for which condition data were only obtained for single value of L_T .) Although the slopes of the regression lines here are lower than in Figure 7.15, the Spearman correlation coefficient is significant ($p < 0.05$) for $L_S - L_T = -10$ and highly significant ($p < 0.001$) for $L_S - L_T = 0$ and 10 dB. The correlation is not significant for $L_S - L_T = 20$ dB, for which condition only two values of L_T were used. (In addition, many of the peaks of the curves for the condition of $L_T = 40$ dB and $L_S = 60$ dB pe SPL are affected by the suppression ceilings, which may have obscured the true values of Δt_{pk} .)

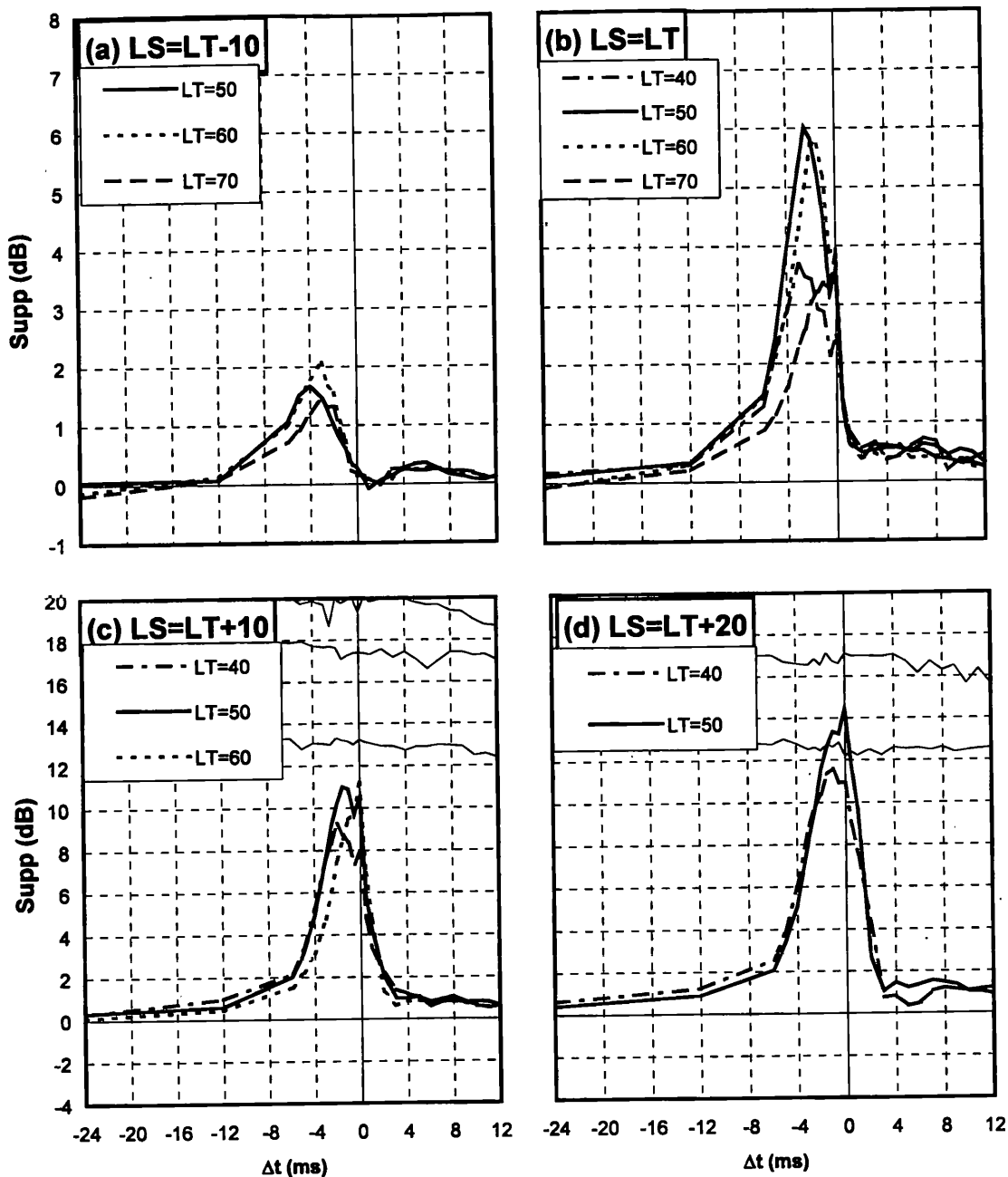


Figure 7.22 (a) through (d). Mean suppression versus Δt curves grouped by $L_S - L_T$. Within each panel successive curves show the effects of concomitant increases in both click levels. Suppression ceilings (thin lines) have magnitudes in sequence as per the values of L_T , with higher ceilings for higher values of L_T . Note the change of Y axis scale between panels (b) and (c). Data are for the whole CEOAE waveform, i.e. the 6-24 ms segment.

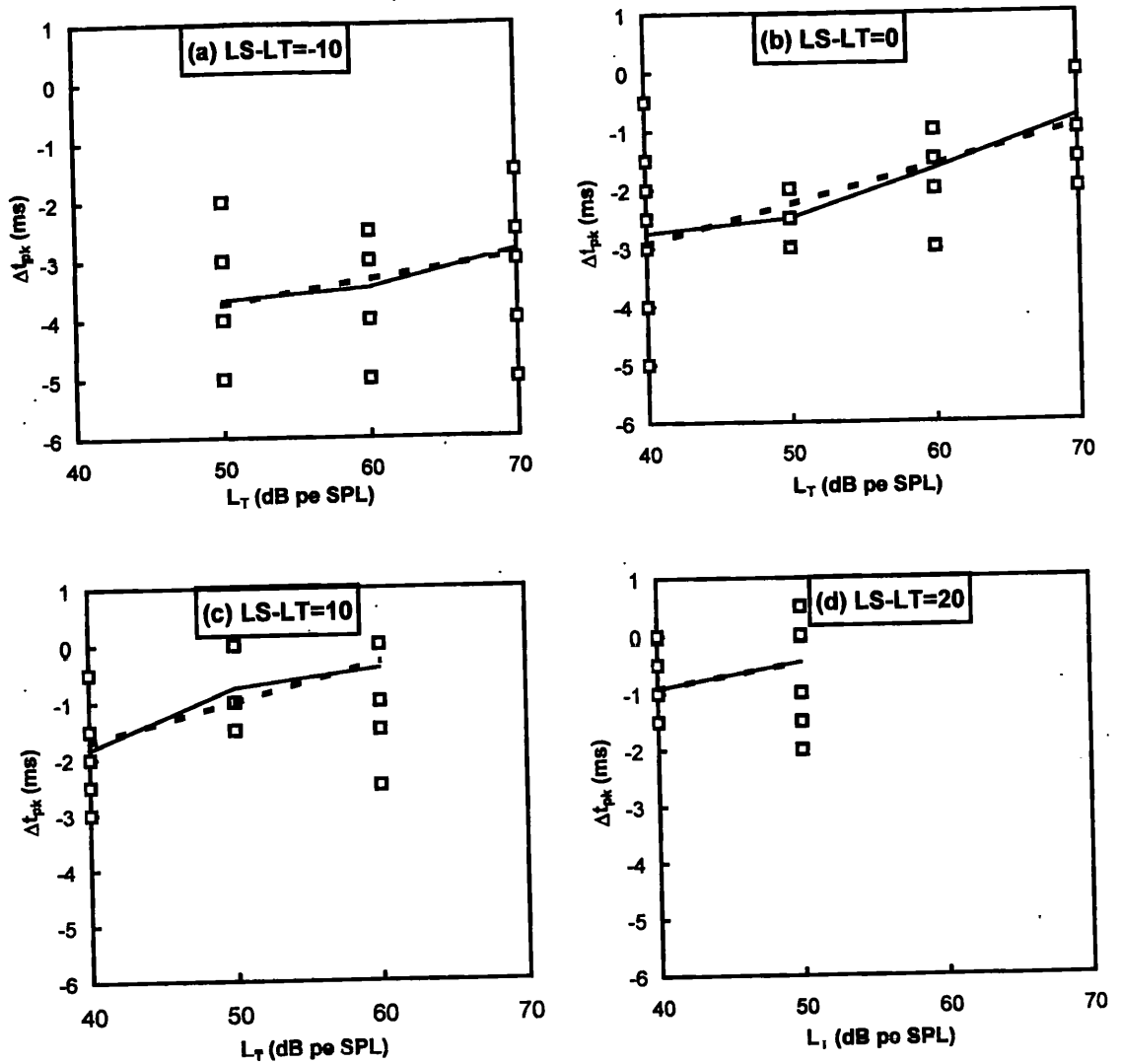


Figure 7.23. Dependence of position of dominant peaks of individual suppression curves (Δt_{pk}) on the value of L_T within fixed values of $L_S - L_T$. (The plots demonstrate the effects on Δt_{pk} of varying both click levels together.) The format of the figure follows that of Figure 7.15, with solid lines indicating mean values and dashed lines linear-fit trend lines.

Finally, Figure 7.24 shows the influence of the level of the test click, L_T , on individual suppression peak heights, for fixed values of $L_S - L_T$. In contrast to Figure 7.16 (which showed a near “linear” relationship between peak height and $L_S - L_T$), the relationship here is non-monotonic, with generally smaller peak heights at the extreme values of L_T (40 and 70 dB pe SPL) than at the intermediate values (50 and 60 dB pe SPL). As a test for simple correlation is clearly not appropriate here, a repeated measures analysis of variance was performed separately for the data in each panel, with L_T as the independent (within-subjects) variable. A significant relationship ($p < 0.05$) is found for the condition of $L_S - L_T = -10$ dB (panel (a) in Figure 7.24), and a highly significant relationship ($p < 0.005$) for the other three conditions. Note, however, that the relationship in the case of $L_S - L_T = 20$ dB (panel (d)) is suspect, due to the possibility of the suppression ceilings having forced or accentuated the differences in peak heights for the two values of L_T (see Figure 7.22). In the other three cases, where three or more values of L_T are involved, the analysis of variance model also confirms the statistical significance of the “nonlinearity” of the relationship between peak height and L_T evident in Figure 7.24.

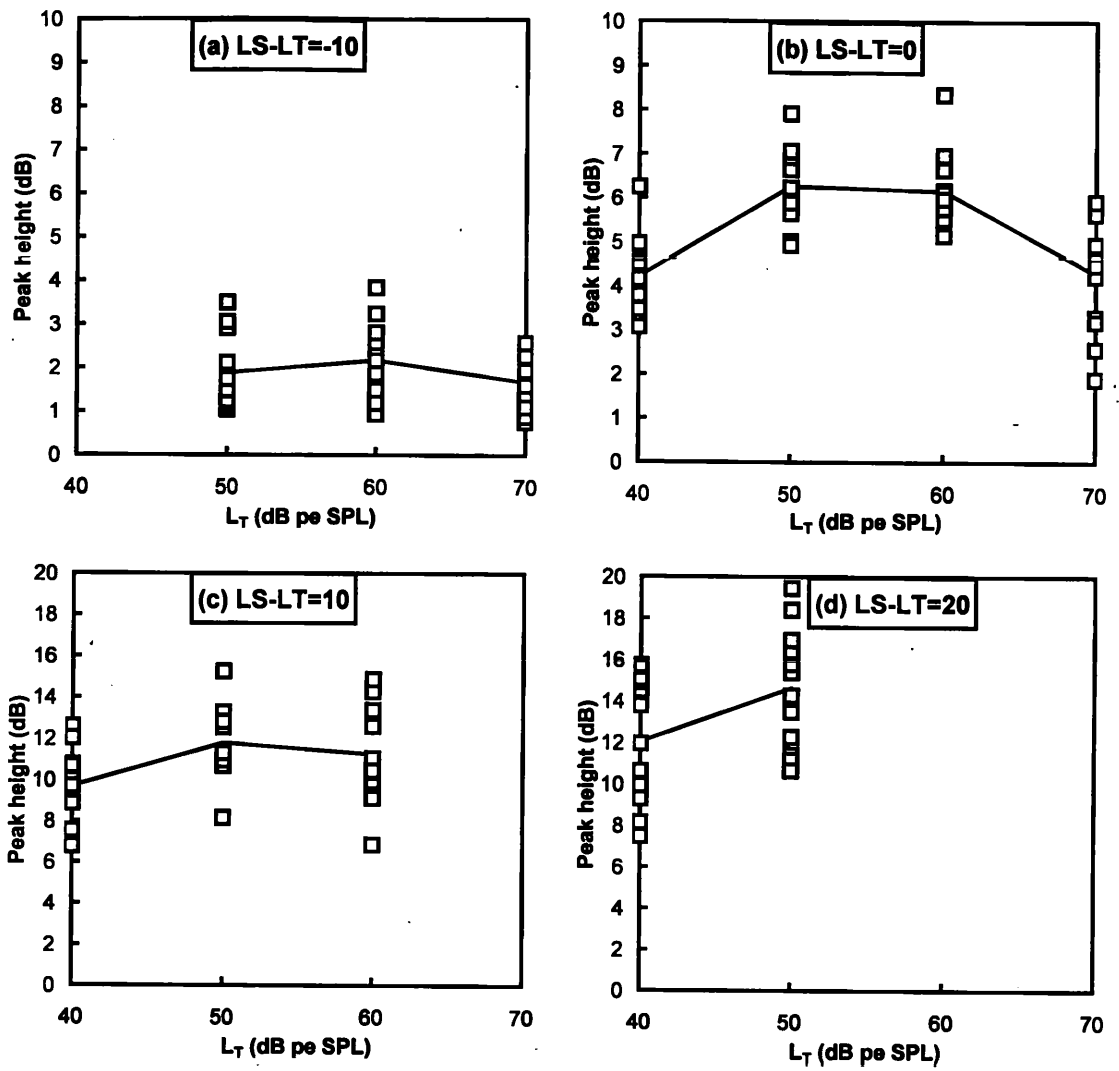


Figure 7.24. Dependence of height of the peaks of individual suppression curves on the value of L_T within fixed values of $L_S - L_T$. The format of the figure is similar to that of Figure 7.23, with solid lines indicating mean values. Note the change of Y axis scale between panels (b) and (c).

7.7 Maximum suppressor-test interval giving nonlinear interactions

This study was not designed primarily to identify the maximum inter-click intervals at which suppression began, and hence relatively coarse step sizes were used at the larger values of Δt (as compared to the lower values that delineated the peaks of the curves). Nevertheless, for comparison with previous data one-sample t-tests were conducted to identify the maximum inter-click interval *for leading suppressors* at which the mean suppression value was significantly greater than zero. No corrections for multiple t-tests were performed here, but the criterion requiring a minimum of 0.6 dB suppression was additionally applied. (This value corresponds to two standard deviations of the differences in amplitudes between independent pairs of *no-suppressor* measurements, as discussed previously in Section 7.2.)

Table 7.1 lists the minimum (negative) values of Δt at which significant suppression was measured for each of the 13 click level conditions. Also indicated is the (mean) value of suppression obtained for this value of Δt . As seen in the table, significant suppression for leading suppressors generally begins at inter-click intervals of 6 to 12 ms. However, for two conditions ($L_T = 40$; $L_S = 60$ and 70 dB pe SPL) suppression is seen for a suppressor leading by as much as 24 ms. This indicates that the 24 ms minimum gap maintained between clicks in successive time epochs in the averaging paradigm (selected on the basis of pilot measurements) would not have been sufficient to prevent interactions between clicks in successive epochs for these two conditions. However, the errors introduced are likely to have been small, as the major effects discussed for these two conditions are associated with magnitudes of suppression that are substantially greater than the corresponding ones listed in Table 7.1. It is also likely

that an experimental design utilising smaller steps sizes for these relatively large values of Δt would show that significant suppression begins at somewhat larger inter-click intervals than indicated here.

L_T (dB pe SPL)	L_S (dB pe SPL)	Min(Δt) (ms)	Suppression (dB)
40	40	-6	1.3
40	50	-12	1.0
40	60	-24	0.6
40	70	-24	1.0
50	40	-6	1.0
50	50	-6	1.5
50	60	-12	0.6
50	70	-12	0.9
60	50	-6	1.0
60	60	-6	1.5
60	70	-6	1.5
70	60	-6	0.7
70	70	-6	0.9

Table 7.1. Minimum Δt values (representing maximum inter-click intervals for leading suppressors) at which significant suppression of the whole-waveform CEOAE was observed, for each click level condition. The corresponding suppression values are also listed ($p < 0.01$ in all cases).

As shown previously, suppression due to following suppressors is highly dependent upon waveform segment and does not vary smoothly with changes in Δt , or in general tend to zero as Δt increases. It is therefore not meaningful to identify maximum values

of Δt at which significant suppression occurs for following suppressors. It is however noted that substantial suppression is seen in at least some waveform segments (particularly the late ones) at *all* positive values of Δt used in the present study.

8. Discussion – Experiment One

8.1 Comparison with level function-based model

Chapter 4 described a model of the click suppression phenomenon in which suppression was generated purely by the action of a compressive level function upon a pair of signals that partially overlapped in time. Curves of suppression versus Δt for various degrees of level function saturation were derived (Figure 4.6), which had the characteristic feature of maximum suppression at $\Delta t = 0$. In contrast, the corresponding curves for the measured suppression data presented earlier show, in the main, suppression maxima at values of $\Delta t < 0$. Furthermore, the position of these maxima is dependent upon the levels of the test and suppressor clicks in a systematic manner (Figure 7.6, Figure 7.22) that is not explicable by the model of Chapter 4.

The amount of suppression measured in several individual instances of equilevel test and suppressor clicks was also greater than the theoretical limit of 6 dB that could be generated by a fully-saturated level function (Equation 4.1). This limit is also exceeded in the mean suppression for all subjects measured within some 3-ms waveform segments – see e.g. Figure 7.11 (b) and (c).¹⁶

¹⁶ It may theoretically be possible to calculate the amount of suppression due to level function nonlinearity alone for each individual ear, and thus the “excess” suppression actually obtained. However, such calculations are not feasible in the absence of reliable estimates of the spatial and temporal patterns of the appropriate excitation functions within the cochlea. Indeed, given the variation of CEOAE patterns across subjects, these excitation functions may also be highly variable from subject to subject.

It is therefore clear that the model of suppression based only upon level function nonlinearity as described does not adequately explain the click suppression phenomenon, particularly for leading suppressors, as measured in this study. However, the tendency for the positions of the suppression maxima to approach $\Delta t = 0$ at the higher values of L_T and of $L_S - L_T$ may be an indication of a restricted role of level function nonlinearity in generating click suppression in these conditions.

The model described in Chapter 4 also relied upon two key assumptions – namely that the net CEOAE measured in the ear canal was composed of frequency components that were generated within essentially independent channels; and that the nonlinear effects within such channels dominated over any nonlinear effects *between* channels. These assumptions are broadly consistent with the data of many workers (e.g. Kemp and Chum, 1980; Probst *et al.*, 1986; Tavartkiladze *et al.*, 1994; Xu *et al.*, 1994; Prieve *et al.*, 1996; Ueda, 1999), although evidence to the contrary has been reported by Sutton (1985) and Withnell and Yates (1998) (see Section 2.4.1).

The primary conclusion that may be drawn from these data is therefore that click suppression cannot be explained in terms of a static, compressive nonlinearity operating at each of several independent frequency channels. Alternative explanations are considered in Section 8.3 below.

8.2 Comparisons with findings of other workers

The results obtained in the study are broadly consistent with the basic findings with respect to CEOAE suppression by an additional click obtained by previous workers. These are that suppression increases with reducing inter-click interval, as reported by Kemp and Chum (1980), Tavartkiladze *et al.* (1994), Lina-Granade and Collet (1995), Tavartkiladze *et al.* (1996) and Kevanishvili *et al.* (1996), and with increasing level of suppressor click relative to test click (Kemp and Chum, 1980; Kevanishvili *et al.*, 1996).

However, the key finding of a maximum of suppression occurring (for most conditions) for a Δt value of less than zero has not been reported by any of the previous authors. (Indeed, none bar Kemp and Chum (1980) included the condition of $\Delta t = 0$ in their tests, which would have increased the possibility of observing this result.) As the finding is consistently found across a range of conditions and subjects in the present study, this apparent discrepancy is discussed in detail below.

Most of the data of Kemp and Chum (1980) were obtained using suppressor clicks that were substantially larger than the corresponding test clicks. As discussed previously, at the higher values of $L_S - L_T$, the suppression maxima for the data in the present study tended to be at Δt values approaching zero. The inter-subject variability evident from the present study and the relatively small numbers of subjects used in Kemp and Chum's preliminary study may therefore account for the apparent discrepancy. However, it is interesting to examine the solitary set of data presented by those authors that included equilevel test and suppressor clicks (their "equi-response" data of Fig. 7(a), p.225). A close examination of this figure reveals that the curve for test and

suppressor clicks both at 30 dB SL appears to show greater suppression between Δt values of -1 and -3 ms than at 0 ms. The difference in the magnitude of suppression would be approximately 1 dB, assuming a CEOAE level function slope of 0.5 dB/dB. As these data are for a single ear and the difference is small, its validity may have been questionable and Kemp and Chum (1980) do not make mention of it in the text of their paper.

In both Tavartkiladze *et al.* (1994) and Tavartkiladze *et al.* (1996) a single pair of click levels was used, i.e. a suppressor click 26 dB above the test click. Again, it is likely from the present data that the suppression maxima in those studies would occur at Δt values close to zero and therefore their results are not inconsistent in this regard. Interestingly, for one of the two ears for which data are shown by Tavartkiladze *et al.* (1994) (Fig. 8(B), p.202), there is evidence of a peak at Δt (approximately) -2 ms, with slightly *less* suppression at -1 ms (the condition of $\Delta t = 0$ was not included). However, this is for the ear in their study reported as having an SOAE, which gave somewhat atypical results (see Section 2.2.1). The amplitudes of the CEOAEs involved are also close to the noise levels plotted and, as in the case of Kemp and Chum (1980), the validity of the result from a single ear in their sample may have been questionable. Tavartkiladze *et al.* (1994) do not discuss this point and the thrust of their discussions imply suppression uniformly reducing as inter-click interval is increased (for the low values of inter-click interval involved here).

In contrast, all of the data of Lina-Granade and Collet (1995) were obtained using equilevel clicks, and these authors also conducted a much more detailed study for this particular condition than Kemp and Chum (1980). They may therefore have been

expected to observe the result of a suppression peak at a non-zero value of Δt . Indeed, the authors note that the suppression they measured “levelled off” between -2 and -1 ms. However, they did not include the condition of $\Delta t = 0$ and further, their Δt step size of 1 ms was slightly coarser than the one used in the present study (0.5 ms in this region). In addition, in the experimental design of Lina-Granade and Collet (1995), the *no-suppressor* (reference) condition was presented only once in each experiment, rather than interleaved with each *suppressor* condition as in the present study. It is likely that their design resulted in poorer sensitivity and reliability of the suppression measurements. All of the above factors may have contributed to these authors not observing the result reported in the present study. Although they do note the “levelling off” mentioned above in presenting their results, they do not discuss it further.

Kevanishvili *et al.* (1996) also included an equilevel test condition in their study, and a further condition in which L_S was 10 dB *less* than L_T (at which, in the present data, the suppression peak was maximally distant from $\Delta t = 0$). However, they only measured suppression at a single value of Δt (5 ms leading) for these click levels. They did conduct measurements over a range of values of Δt for $L_S = L_T + 10$ dB (at which suppression maxima at $\Delta t < 0$ were observed for most, but not all, of the data in the present study). Only four Δt values were used however, i.e. suppressor leading by 2.5, 5, 7.5 and 10 ms. These steps would have been too coarse to identify the peaks observed in the present study.

None of the above authors, bar Kemp and Chum (1980), conducted a sufficient range of measurements that would have allowed them to observe the other important feature reported here with regard to the maxima of the suppression curves – i.e. the shifts

towards $\Delta t = 0$ with increasing $L_S - L_T$. Once again, the “equi-response” data presented by Kemp and Chum (1980) representing data for a single ear (Fig. 7(a), p.225) shows evidence of this trend, although it is not commented upon. (However, another figure showing similar data for a different ear (Fig. 6(a), p.224) does not show this tendency.)

Neither Kemp and Chum (1980) nor any of the other authors obtained data on the smaller effect observed here of a rightward shift of the suppression maxima as L_T alone was increased (with $L_S - L_T$ constant).

While the present data indicate that the dominant influence upon the magnitude of suppression relating to click level is the level of the suppressor *relative* to the test click ($L_S - L_T$), a small but highly significant influence of L_T alone (for fixed values of $L_S - L_T$) is also found. Interestingly, this relationship is non-monotonic, with greater suppression for intermediate values and less suppression for both the lowest and highest values of L_T used. Such a non-monotonic variation of degree of nonlinearity with level is in striking contrast with the behaviour of the CEOAE level function, for which a uniformly increasing degree of nonlinearity with click level is typically reported. It is noteworthy, however, that these findings of the present study are qualitatively consistent with direct measures of BM nonlinearity. The degree of nonlinearity of the BM response has been shown to increase with stimulus level over low to moderate levels, but then reduce again at the highest stimulus levels, both for pure tone (e.g. Ruggero *et al.*, 1992a) and click (Recio *et al.*, 1998) stimuli.

It may also be noteworthy that some authors have reported findings in relation to MLS rate suppression that correspond in part to the above findings on click suppression.

Lina-Granade *et al.* (1997) reported less rate suppression at high click levels than at moderate ones. However, these authors did not utilise stimulus clicks at levels as low as in present study, which showed the converse *increase* in suppression with level at lower click levels. Additionally, Hine and Thornton (1997), who also studied the effect of click level on MLS rate suppression, found no significant differences in suppression with level.

None of the previous authors investigating click suppression conducted measurements over a range corresponding to that in the present study, and consequently this non-monotonic influence of the level of the test click alone has also been unreported in the past literature on click suppression.

Similarly, while the strong influence of L_S on suppression for a fixed value of L_T had been previously reported, no previous authors had conducted measurements over the parameter range used in this project, which revealed that this influence of L_S-L_T on the magnitude of suppression *reduces* at the highest values of L_T .

The examination of suppression within restricted segments of the CEOAE waveforms in the present data showed that the positions of the maxima of the suppression curves do not vary with waveform latency. A similar finding is evident in the data of Kemp and Chum (1980) (Fig. 5(b), p.222), obtained for a single ear with a single test and suppressor click combination. None of the other authors analysed suppression across different waveform segments.

The examination of suppression across waveform segments also showed that the amount of suppression systematically increases with waveform latency for following suppressors, but not for leading suppressors. Kemp and Chum (1980) did not report these findings, but the only similar data they presented (Fig. 5(b), p.222) show a tendency that is broadly consistent with them. Once again, it would have been difficult to attach any significance to the pattern in the data of Kemp and Chum (1980), which were for a single ear.

Kemp and Chum (1980) also did not examine suppression in the very late waveform segments (beyond 13 ms), for which the present study reveals that suppression due to following suppressors may *dominate* over that due to leading suppressors. As a result, their conclusion that significant suppression is not seen for suppressors that follow the test clicks by more than about 3 ms is not borne out by the present data.

There is a further conflict between the findings of the present study and those reported by Kemp and Chum (1980) with regard to the differences between leading and following suppressors. Kemp and Chum (1980) report that the amount of suppression due to a leading suppressor is much less dependent upon the level of the suppressor relative to the test click ($L_S - L_T$) than is the amount of suppression due to a following suppressor. They deem this to be a surprising finding, and regard it as evidence of a “second type of nonlinearity” (in addition to the static, compressive nonlinearity that they regard as the main source of the suppression phenomenon). The data in the present study exhibit exactly the opposite pattern – suppression due to a *following* suppressor is far less dependent upon $L_S - L_T$ than that due to a leading suppressor. The main source of this discrepancy may be in the noise floor in the data of Kemp and Chum (1980). An

examination of their Fig. 6(a) (p.224) suggests that this noise floor may have limited the amount of suppression measured for leading suppressors at all suppressor levels. However, for following suppressors, the amount of suppression is initially small and therefore not limited by the noise. Substantial growth in suppression is therefore seen as suppressor level is increased for following suppressors, but not for leading ones. A further contributing factor to the discrepancy between the two studies might be the rightward shift in suppression peak position with L_S-L_T , which was not detected by Kemp and Chum (1980). Had this shift applied to their data, its effect would have been to maintain relatively constant suppression along the falling slopes of the suppression curves for leading suppressors, along which most of their suppression values were measured.¹⁷

Tavartkiladze *et al.* (1994) were the only previous authors to report a link between the amount of suppression and waveform latency. They reported that suppression for *leading* suppressors increased with latency, in contrast to the finding in the present study. However, their conclusion appears to be based on an examination of the CEOAE waveforms, rather than on a formal quantification of suppression within waveform segments. Furthermore, the support for this finding in one of the two waveforms that the authors present (ear A in Fig. 8, p. 202) appears debatable. Finally, the assumption implicit in the technique of Tavartkiladze *et al.* (1994), that the CEOAE evoked by their leading click was not suppressed by the following click, may have contributed to the

¹⁷ Note that the plots of suppression versus Δt presented by Kemp and Chum (1980) are *inverted* relative to those of this study. The falling slopes referred to above correspond to rising slopes in the curves of the present study.

discrepancy here, particularly as the present data show that the later waveform segments are *increasingly* suppressible by a following suppressor click.

Tavartkiladze *et al.* (1994) were also the only previous authors to report *enhancements* (in four of five ears tested) of the CEOAE under the influence of an additional click. However, the enhancements they observed were for leading suppressor clicks (as were all their data) and were described as an “overshoot” of recovery of the CEOAE from suppression. Such enhancements were not observed for any ear in the present data, in which enhancements were only observed for following suppressor clicks. CEOAE enhancements in the present study were also usually associated with local waveform changes, as discussed previously, whereas in the examples presented by Tavartkiladze *et al.* (1994) (Fig. 8, p. 202) no such changes are apparent. The differences in the measurement technique noted previously would appear to be the most likely source of the discrepancy here with respect to CEOAE enhancements due to leading suppressors.

Finally, Tavartkiladze *et al.* (1994) were unique amongst previous authors in reporting a “second phase of suppression” in one subject at large negative values of Δt (up to -20 ms). The present study recorded no such observation – suppression for leading suppressors always reduced smoothly towards zero as inter-click interval was increased. It should be noted however that this atypical subject of Tavartkiladze *et al.* (1994) was the only one to exhibit a synchronised SOAE, and such subjects were excluded from the present study.

As previously discussed, enhancements of CEOAE amplitude in the present study were usually accompanied by local changes in the CEOAE waveform. None of the previous

authors have reported observing any waveform changes under the influence of a suppressor click. Kevanishvili *et al.* (1996) specifically report that no changes in phase or latency occurred, from which it may also be inferred that no changes in the structure of the waveforms occurred.

All of the previous authors have estimated the maximum inter-click intervals for which measurable suppression occurs, with values ranging from 4 to 9 ms. However, Lina-Granade and Collet (1995) were the only ones to attempt rigorously to identify these boundaries, by testing for the significance of the effect at a range of values of Δt . Whole-waveform CEOAE amplitude measures only were used. For leading suppressors, their finding of an effect commencing at $\Delta t = -9$ ms is consistent with the value obtained here of -6 ms for comparable equilevel clicks (Table 7.1), given that the next value used in the present study was -12 ms. For following suppressors, Lina-Granade and Collet (1995) observed (weakly) significant suppression beginning at 9 ms, but not at 6 ms and significant suppression again at 3 ms only. Those authors' neglecting to examine suppression within restricted time segments of the CEOAE waveforms would undoubtedly account for their failure to observe stronger effects for following suppressors. In the present study, substantial suppression is seen in such waveform segments at all positive values of Δt used.

The finding that significant suppression may be obtained (for some click level conditions) for a suppressor click that leads the test click by as much as 24 ms may be regarded as surprising, based on previous work of this nature. Its implications are further discussed in the following section.

8.3 Implications for mechanisms of suppression

The preceding results and discussion indicate that the simple model of click suppression based only upon CEOAE level function nonlinearity does not adequately account for the experimental data. It is therefore concluded that the click suppression reported here is not simply a reflection of level function nonlinearity, and alternative mechanisms for the phenomenon must be considered. The discussions so far have also implicitly allowed for the possibility that suppression due to leading and following suppressors may arise from the same mechanism. As shown in Chapter 4, level function nonlinearity can generate suppression in either case. However, the rejection of the level function model as the primary mechanism of click suppression, as well as the characteristics of the data presented in previous sections suggest that different mechanisms are likely to be involved when the suppressor either leads or follows the test click. This likelihood is reflected in the following discussions.

One possible mechanism that was raised and discounted by Tavartkiladze *et al.* (1994) (in relation to leading suppressors) was of an ipsilateral efferent effect, similar to the efferent effect on CEOAEs observed under contralateral stimulation (Collet *et al.*, 1990). The argument used by Tavartkiladze *et al.* (1994) was that the latency of the phenomenon, being “within 5-7 ms” was less than the minimal latency of the olivocochlear efferent response. This argument is not strictly valid, as the measurements of Tavartkiladze *et al.* (1994) (as in the case of the present study) were made with test and suppressor click pairs presented within continuous *streams* of clicks, rather than in (pair-wise) isolation. Nevertheless, it is difficult to conceive of an efferent-related explanation that could result in the marked differences in the amount of

suppression seen between, for example, Δt values of -4 and -2 ms, within such click streams. The fact that the magnitude of suppression for leading suppressors is also so much larger than that reported for efferent suppression under *either* ipsilateral or contralateral stimulation (e.g. Collet *et al.*, 1990; Veuillet *et al.*, 1991; Berlin *et al.*, 1995b; Tavartkiladze *et al.*, 1996) also argues against any significant efferent contribution to the effects observed here.

For following suppressors, the amount of suppression in the whole-waveform measures is of a similar magnitude as reported for efferent suppression, and further appears relatively insensitive to changes in Δt . However, the examination of such suppression within restricted waveform segments shows a sensitivity and a marked non-uniformity with respect to Δt , and a magnitude of suppression that is not consistent with reports of efferent suppression (Collet *et al.*, 1990; Veuillet *et al.*, 1991; Berlin *et al.*, 1995b; Tavartkiladze *et al.*, 1996).

Similar arguments in relation to the sensitivity of the suppression phenomenon to minor changes in Δt , and further, its marked dependence on waveform segment in the case of following suppressors, can be used to discount the possibility of an involvement of a middle-ear reflex.

It therefore follows that the primary mechanisms of click suppression, for both leading and following suppressors, are likely to lie entirely within the cochlea.

8.3.1 Leading suppressors

Two key assumptions were made in postulating the simple model of suppression based on level function nonlinearity. These were that:

- (i) The net CEOAE measured in the ear canal was composed of frequency components that were generated within essentially independent channels.
- (ii) The nonlinear effects within such channels dominated over any nonlinear effects between channels.

These assumptions represent a historical view that is supported by the data of many workers (e.g. Kemp and Chum, 1980; Probst *et al.*, 1986; Tavartkiladze *et al.*, 1994; Xu *et al.*, 1994; Prieve *et al.*, 1996; Ueda, 1999).¹⁸ Some contradictory evidence has been reported by Sutton (1985) (discussed in Section 2.4) and by Avan and co-workers (Avan *et al.*, 1991; Avan *et al.*, 1993), who reported that damage to basal regions of the cochlea can have a secondary influence on CEOAEs at frequencies corresponding to more apical cochlear locations.

However, the most direct challenge to the above assumptions arises from the work of Yates and co-workers (Withnell and Yates, 1998; Yates and Withnell, 1999). Based on their work on CEOAEs measured in guinea pigs, those authors argued *against* the

¹⁸ It should be noted that Probst *et al.* (1986) and Xu *et al.* (1994) both observed relatively minor departures from the overall tendency of independence of generator channels.

traditional notion of a one-to-one relationship between frequency components within the (broadband) click stimulus and the CEOAE response. They suggested that a large portion of the CEOAE component at any given frequency was composed of intermodulation energy, generated by stimulus components at *different* frequencies. Their argument was supported by findings of complex behaviour of the CEOAE (including enhancements) under the influence of a pure-tone suppressor, which was not consistent with the one-to-one relationship mentioned above. Implicit in the proposal of those authors is the notion that a given CEOAE component is composed of a somewhat random summation of a large number of sub-components, generated at different sites within the cochlea.

While the data of the present study for leading suppressors do not directly contradict the arguments of Withnell and Yates, their proposal would suggest a far more complex pattern of suppression than is seen in the present study. For example, the data in the present study show that the maxima of the suppression curves occur at the same value of inter-click interval for all the segments within the CEOAE waveform. It is difficult to reconcile this observation with a hypothesis that each such waveform segment is composed of a random summation of (different) nonlinear interactions over a widely-dispersed region of the cochlea. A similar difficulty would be encountered in reconciling the findings of the present study with the arguments of Sutton (1985), who also suggested some type of widely (spatially) distributed CEOAE generation process.

Thus, even if assumptions (i) and (ii) above on CEOAE generation were to be overturned, this (coupled with level function nonlinearity) does not of itself account for the pattern of experimental data obtained.

It seems most likely, rather, that the effect of a leading suppressor is due to a disturbance of the CEOAE generator elements from their “resting state” prior to the excitation by the test click. It is hypothesised here that this disturbance is directly related to the *envelope* of displacement along the BM in response to the suppressor click. As CEOAEs are thought to be dependent upon the mechano-electrical activity of the OHCs, it is possible that the capacity or performance of the OHCs in this regard is reduced under the influence of the prior disturbance due to the suppressor. It is hypothesised that this disturbance from the resting state would be related to the envelope of the displacement, rather than the instantaneous (oscillatory) displacement in response to the suppressor, due to:

- (i) The insensitivity of the phenomenon to the polarity of the suppressor click, as shown in Chapter 5.
- (ii) The relative smoothness of the individual suppression curves, for Δt steps as small as 0.5 ms.

In both these cases, complete inversions in the phase relationships between test and suppressor disturbances would be expected – the suppression generated may be expected to be markedly sensitive to these, were the mechanism related to the instantaneous rather than the envelope of displacement of the BM.

This general hypothesis can also qualitatively account for the key feature of these data, of peak suppression for leading suppressors occurring at progressively shorter inter-click

intervals, as the level of the suppressive click increases relative to that of the test click. For low to moderate click levels, the BM response to a click (e.g. Ruggero, 1994; Recio *et al.*, 1998) has the form of a roughly symmetrical tone burst, with an envelope that peaks a few cycles following the tone burst onset. However, as click level is increased, the early section of this response tone burst grows far more rapidly than the later ones, with the result that the envelope is skewed and peaks increasingly close to the response onset. Thus at any given CEOAE generator site, the maximum suppressor-evoked disturbance would occur sooner as suppressor level is increased. Assuming that the peak suppression occurs when the generator elements are maximally biased at the *onset* of the (following) test-evoked disturbance, this peak would occur at shorter suppressor-test delays as the suppressor level is increased relative to that of the test click. The maxima of the curves of suppression versus Δt would therefore shift towards zero, as found in the experimental data.

The above hypothesis is also qualitatively consistent with the weaker feature of a slight shift of suppression maxima towards $\Delta t = 0$ as *both* the click levels are increased together. Along with the reduction in latency of the response peaks in BM click responses, increases in click level are also reported to give a smaller reduction in latency of the response *onsets* (e.g. Ruggero *et al.*, 1992b; Ruggero, 1994). Thus as a pair of clicks are jointly increased in level (as in the present experiment), the onsets of the responses to both clicks would shift to the left along the time axis, but not as much as the peaks of the responses. This would result in a reduction in the delay between the “suppressor” peak and the “test” onset; however this reduction would be less pronounced than that resulting from increases in suppressor level for a *fixed* level of test click.

There remains a considerable gap in current knowledge over the generator processes of CEOAEs and their relationship to click responses within the cochlea (e.g. Kemp, 1997). Thus any refinement of the above hypothesis towards the exact mechanism whereby the disturbance due to the suppressor click may suppress the CEOAE evoked by the test click is necessarily speculative. Given the existence of a static compressive I-O nonlinearity however, an economical hypothesis would involve a *modification* of the static nonlinearity by the suppressor-evoked disturbance, rather than invoking a new type of nonlinearity.

Such a modification could broadly be of one of two types:

(a) A reduction of the gain of the static I-O function. In this case, suppression follows directly from the attenuation of the output signal relative to that arising from the original I-O function.

(b) A shifting of the “operating point” of the static I-O function. Suppression in this case would be due to the indirect effect of a reduced slope of the I-O function over the same range of input signal.¹⁹

¹⁹ Note that the proposal here is of a shift in the operating point *between* the *no-suppressor* and *suppressor* conditions. This is in contrast with the discussion (Chapter 4) of an I-O curve in which the operating point is “shifted” from the central (maximum slope) position, but is constant for both *no-suppressor* and *suppressor* conditions.

Although the shift of operating point may be regarded as a more complex explanation here, there have been other discussions in the literature of the importance of the operating point of the cochlear amplifier in relation to nonlinearity in the cochlea (e.g. Patuzzi *et al.*, 1989; Cheatham and Dallos, 1994; Lukashkin and Russell, 1998). (Amongst these authors, Lukashkin and Russell take a somewhat atypical view, in describing a model of two-tone suppression within hair cell potentials that depends on the behaviour of the hair cell transducer I-O function *at* the operating point, rather than when driven into its saturating region.) In the otoacoustic emission literature, Frank and Kössl (1997) relate the behaviour of DPOAEs to the position of an operating point along a nonlinear Boltzmann function.

It is difficult to make comparisons between these previous studies and the present one, partly as the previous ones relate to nonlinear behaviour under the influence of stationary, jointly-presented signals or a well-defined low frequency “bias” signal, rather than for temporally separated transients. However, such studies do provide precedents for the hypothesis presented here to account for the effects of a leading suppressor click.

Both of the above types of modifications of the static I-O functions underlying CEOAEs have also been hypothesised as being involved in the observed effects on cochlear mechanics of efferent activation (Patuzzi and Rajan, 1990). However, in that case the presumed modifications would be initiated by neurotransmitter activity rather than biomechanical activation, and in the case of efferent effects on CEOAEs, the amount of suppression is much smaller than that observed in the present study.

One means of distinguishing between the two possible mechanisms (a) and (b) above might be by an examination of the distortions or changes in the structure of the waveforms in the *suppressor* condition relative to the *no-suppressor* condition. Some distortion in the output waveform would necessarily be present in the case of the “operating point shift” mechanism, but it may or may not be present in the case of a “reduction of gain” mechanism. (While it may be more likely that the gain is reduced symmetrically in the positive and negative directions, this need not necessarily be the case.) A similar argument was made by Cheatham and Dallos (1994) in relating waveform distortions they observed in intracochlear potentials (in response to a probe tone burst) to the “biasing” effects of an intense low-frequency bias tone. No gross waveform distortions were evident in the data obtained for leading suppressors in the present study, arguing against the operating point shift mechanism. However, the complex structure of the CEOAE waveforms may well have masked any such distortions, should they have been present.

As stated, a hypothesis of a suppression mechanism that is related in some way to the underlying static I-O nonlinearity of the CEOAE has the benefit of being scientifically parsimonious. It should be noted, however, that the amount of suppression for leading suppressors is not strongly dependent upon waveform segment (in contrast with I-O nonlinearity). This would imply that these hypothesised effects on the underlying I-O functions are not equivalent across waveform segment. For example, in the case of the “reduction of gain” mechanism, it would appear that there is less effect on the gain of the I-O functions that are already more compressive (later waveform segments) in the undisturbed condition.

Thus, although some suggestions have been made here on the underlying mechanisms involved in the generation of click suppression as measured in the present study, further work is required to derive a more specific explanation of the findings. One potentially useful approach would involve a more complex modelling study based on models and experimental data pertaining to physiological measurements of BM click responses and nonlinearities. Although such a study would need to make appropriate scaling transformations for the human cochlea and relevant frequency ranges, it may allow an assessment of whether the mechanisms suggested here could account for the data in a quantitative manner.

Further experimental work that may also be of value in investigations of this nature would include suppression measurements similar to those of the present study, but using tone burst-evoked OAEs (TBOAEs) rather than the CEOAEs used here. TBOAEs not only have a less complex frequency content than CEOAEs, but are also held to arise from more localised sites within the cochlea. Their use may therefore allow for more specific, and hence possibly more informative, investigations.

8.3.2 Following suppressors

The rejection of the simple level function model of click suppression was based primarily on the data for leading suppressors. Given that the static compressive I-O function underlying level function nonlinearity does generate click suppression as measured here (Chapter 4), it remains a likely candidate mechanism for such suppression in response to following suppressors. Although more complex suppression curves (including enhancements) are observed in the experimental data than in the

model of Chapter 4, these may be explained by allowing for a physically and temporally distributed CEOAE generation process.

As discussed previously, it is generally held that different frequency components of the CEOAE are generated at different sites (and times) within the cochlea, and the net response is a summation of these components. Some overlap between these components as measured in the ear canal may be expected, and is indeed indicated by the relatively complex structure of CEOAE waveforms as compared to those of tone burst-evoked OAEs (e.g. Probst *et al.*, 1986). Bearing in mind that the suppressor click in this case occurs *after* the test click (that evokes the CEOAE of interest) it can be hypothesised that different generator sites are affected differently, depending upon the temporal relationship between test and suppressor disturbances at each. Thus, as argued in a different context by Withnell and Yates (1998), a complex net pattern of suppression may be observed (including enhancements) depending upon the original interactions between the multiple CEOAE components and the variable effects of the suppressor on each. It should be noted however that the present argument does not necessarily imply significant *nonlinear* interactions across frequency channels as suggested by Withnell and Yates (1998). The complex net pattern of suppression referred to here could equally arise out of the complexity of the linear interactions between multiple CEOAE components, combined with nonlinear interactions that are largely within individual frequency channels.

Thus, the data of the present study for following suppressors are most parsimoniously explained on the basis of the temporally and physically distributed nature of the CEOAE generation process, without necessitating a challenge to the model based on a level

function nonlinearity and its associated assumptions. Consistent with this possibility is the finding of the present study that suppression in the case of following suppressors is strongly dependent upon waveform segment, in a manner that mirrors the level function nonlinearity.

It is, of course, possible that aspects of the patterns of suppression for following suppressors indicate that the assumptions made in connection with the level function model of click suppression are incorrect. This possibility needs to be acknowledged particularly as these assumptions have been disputed to a lesser or greater extent by authors such as Withnell and Yates (1998), Sutton (1985) and Avan *et al.* (1997). However, the present study was not designed principally to test these arguments and the results obtained cannot resolve them. Thus, while the pattern of suppression as seen in the present study may well reflect a distributed CEOAE generation mechanism as suggested by those authors (and consequently violations of the assumptions mentioned above), it is not necessary to invoke such a mechanism to explain the data observed in this study.

The use of TBOAEs in future studies of this nature, as suggested above for leading suppressors, may be of even greater value in further studying the effects of following suppressors. As TBOAEs represent cochlear responses that are less dispersed than CEOAEs in the frequency, spatial and temporal domains, they may allow a clarification of some of the issues discussed in the preceding paragraphs. The use of a pair of TBOAEs of *different* frequencies in a paradigm similar to the one of the present study may additionally provide a powerful means of investigating the fundamental issue of across-channel nonlinear interactions discussed above and in Section 2.4.

8.4 Implications for cochlear responses to transient signals

The data on click suppression obtained in the present study may also have wider implications for aspects of the generation and measurement of CEOAEs and for cochlear responses to transient signals generally.

Firstly, the data presented indicate that some suppression may be effected by a suppressor click as much as 24 ms in advance of a test click. This implies that the mechanical response of some part of the BM must persist for at least 24 ms following the suppressor click, and at an intensity sufficient to interact nonlinearly with the disturbance due to the test click. Most data on direct measures of BM click responses in laboratory animals indicate responses of somewhat shorter duration, typically lasting 5-10 ms (e.g. Ruggero, 1992; Cooper and Rhode, 1996a; Recio *et al.*, 1998). However, occasional instances of considerably longer-lasting responses from “exceptionally sensitive preparations” have also been reported (e.g. Recio *et al.*, 1998, p. 1975). It is possible that most physiological data on click responses in laboratory animals somewhat underestimate the duration of corresponding responses in the undamaged human cochlea.

Furthermore, the inter-click interval of 24 ms is also similar to the duration of the CEOAE response itself, as recorded in the ear canal. The fact that (a) small but significant suppression can be observed at this inter-click interval, and (b) that the long-latency “tail” of the response may be suppressed by a following suppressor (positive Δt) suggest that the major portion of the duration of a CEOAE response corresponds to a

period of sustained, nonlinear vibration within the cochlea. This contrasts with an alternative scenario in which a significant portion of the duration of the response corresponds to a linear propagation (in either the forward or reverse direction) of intracochlear vibrations. The conclusion that may be drawn is therefore that the reverse propagation within the cochlea of a CEOAE is either an extremely rapid or a substantially nonlinear process. The implication of a nonlinear reverse propagation process is not entirely expected. Although the concept of a “reverse travelling wave” has been mooted in connection with the generation of OAEs (e.g. de Boer, 1991, chapter 5), such a wave would represent a substantially “off-characteristic frequency” disturbance, and the nonlinearity of the travelling wave is primarily associated with characteristic frequency disturbances (e.g. Patuzzi, 1996).

The demonstration that click suppression as measured in the present study is sensitive only to *nonlinear* signal interactions (see Figure 5.3; also Figure 7.7 and Figure 7.8) suggests an additional means for the discrimination of a true physiological response and linear artifacts in CEOAE measurements. At present, such a discrimination typically relies on the saturation of the CEOAE level function (as described in Section 2.1). However, the apparent dissociation between level function nonlinearity and click suppression suggests that the two methods may not be equivalent, and there may be benefits of one over the other in some circumstances.

Finally, the findings of the present study may have implications for studies of the psychoacoustic masking of one signal by another. Although the possible involvement of direct mechanical suppression (arising from the nonlinearity of BM mechanics) in simultaneous masking is recognised, suppression is generally assumed to play an

insignificant role in masking between non-simultaneous signals, and other mechanisms are thought to underlie non-simultaneous masking.²⁰ For example, Oxenham and Plack (1998) conducted masking experiments using a silent interval of just 2 ms (defined for the electrical envelopes of the signals) between a forward masker and a test signal. Although they discuss the possibility of BM suppression (caused by “ringing in the auditory filters”) influencing their data, they conclude that peripheral interactions probably played no role in their experiments. However, the present study indicates considerable CEOAE suppression for inter-click intervals as large as 5 to 10 ms. This may call into question the assumption that suppression does not contribute to non-simultaneous masking that involves masker-signal gaps of a few milliseconds or more.

²⁰ The nature of these other mechanisms, however, is still unclear (see e.g. Moore, 1997).

Experiment Two – Accumulation of suppression due to multiple clicks

9. Aims and methods – Experiment Two

9.1 Aims

Experiment Two was designed to address the second major aim of the project – to determine whether the suppression due to *multiple* suppressor clicks accumulated in a simple, additive manner. Such an additivity of suppression had been postulated by Picton *et al.* (1993) in discussing the shortfall (of about 3 dB as estimated by those authors) between single-suppressor click suppression and the suppression observed in recording CEOAEs at high click rates using the MLS technique. While this hypothesis appears reasonable (assuming a direct, intracochlear suppression mechanism in both cases), the suppression due to a single suppressor may well be *reduced* by the presence of an additional suppressor (i.e. “suppression” between the suppressors). A simple accumulation of single-click suppression may not hold in this case. As described in Chapter 2, no data on click suppression due to multiple suppressor clicks have yet been published. Attention was therefore directed to the simplest condition of accumulation of suppression, involving comparisons of the suppression generated by a single suppressor with that generated by a pair of suppressors. It should also be noted that CEOAE recordings using the MLS technique involve equilevel clicks only, and MLS rate suppression has been reported as being not, or only moderately, sensitive to click level (Hine and Thornton, 1997; Lina-Granade *et al.*, 1997). Accumulation involving test and suppressor clicks of equal level was therefore investigated here.

The proposal of an additivity or accumulation of single-click suppression by Picton *et al.* (1993) primarily referred to the suppression due to leading suppressor clicks. This was reasonable, as the arguments of these authors were based on suppression of the whole CEOAE waveform, and the single-click suppression data of Kemp and Chum (1980) (as well as of the present study) showed that it was leading suppressor clicks that were most effective in suppressing the whole CEOAE waveform. If a simple accumulation of click suppression applied, therefore, it would be expected that an accumulation of the suppression due to leading suppressors would be primarily responsible for the greater amount of suppression observed in MLS-recorded CEOAEs. Furthermore, as found in Experiment One of the present study, apart from generally yielding less suppression, the effect of a following suppressor click can be more complex than that of a leading suppressor, with instances of CEOAE enhancement and modification of the waveforms observed.

Therefore, in attempting to establish whether a simple accumulation of single-click suppression applied when multiple clicks were used, the prime focus of Experiment Two was on suppression due to a single leading and pairs of leading suppressors. However, data were also obtained on pairs of following suppressors, and on mixed (one suppressor leading and one following) pairs of suppressors.

9.2 Subjects

Subjects were normally-hearing adults aged between 18 and 35. Written informed consent was obtained from all subjects, who were paid for their participation.

The selection criteria based on conventional audiometric measures were broadly similar to those applied in Experiment One. Pure-tone air-conduction HTLs in the test ear were required to be ≤ 20 dB at all audiometric frequencies between 250 and 8000 Hz. Ear canals needed to be free of obstruction and middle-ear pressures needed to be within ± 50 daPa. Acoustic reflex thresholds of ≤ 100 dB HL were required (using ipsilateral, 1 kHz tone-burst stimuli).

As for Experiment One, only one ear per subject was used in order to obtain an independent data set. Data for Experiment Two were obtained from a total of 20 ears. However, data from three ears were excluded *post hoc* due to the presence of strong synchronised SOAEs²¹ and from a further three ears due to excessive drift in the *no-suppressor* (baseline) CEOAE amplitude. Data are therefore reported here for 14 ears, of which 7 were from female subjects.

In contrast to Experiment One, no low-level click stimuli were used in this experiment (see below) and therefore it was not necessary to exclude any ears on the basis of low-amplitude CEOAEs.

9.3 Test procedures

Preliminary test procedures involving a questionnaire on audiological status, otoscopy, middle-ear measurements, pure-tone audiometry, SOAE screening and measurement of subjective click thresholds were performed as for Experiment One. CEOAE level

²¹ The reasons and criteria for excluding subjects with strong SSOAEs are discussed in Chapter 6.

functions were also measured in a similar manner to Experiment One, but only using click levels of 40, 50, 55, 60, 65 and 70 dB pe SPL.

The click suppression measurements comparing suppression due to a single and a pair of suppressor clicks were then carried out, in a single measurement sequence without removal or refitting of the ear canal probe.

Other than the presentation of an additional suppressor click, the stimulation and recording paradigm was the same as used in Experiment One and described in detail in Chapter 3. Test clicks and the sense of the averaging were alternated in polarity, whereas suppressor clicks were of constant polarity. Both the suppressor clicks were presented via the same output transducer, the other output transducer being reserved for the test clicks only. Preliminary tests confirmed that the addition of the second suppressor click did not compromise the accuracy of the cancellation of the suppressors achieved – i.e. no non-cancellation artifacts were detectable above the recording noise floor.

For these measurements, fixed test and suppressor click levels of 60 dB pe SPL each were used. This represented a moderately high click level, at which clear CEOAEs and suppression would be expected in all normal ears tested, but at which excessive stimulus click artifact or “ringing” would not be expected. A more restricted range of inter-click intervals (Δt) than used in Experiment One was used here, concentrating on Δt values closer to zero, at which generally greater suppression had been observed for single suppressor clicks. All measurements here were conducted with suppressor clicks

presented between -3 and $+5$ ms relative to the test click.²² Within this range, single suppressors were presented at 13 different values of Δt (six negative, six positive and $\Delta t = 0$). From these, 15 pairs of Δt values were chosen to give a broad mix of the three types of suppressor combinations – i.e. both suppressors leading the test click, both suppressors following, and one leading and one following suppressor. These 28 Δt conditions for single and paired suppressors are listed in Table 6.1. Note that although the $\Delta t = 0$ condition was used in the single-suppressor measurements, it was not included in any of the paired-suppressor conditions as it does not represent a condition that can arise in high click-rate (MLS) CEOAE measurements.

Other general aspects of these CEOAE recording procedures followed the procedures established in Experiment One. A minimum delay of 24 ms was always maintained between the last click in one epoch and the first click in the next, in order to minimise interactions between such clicks. Noise rejection limits were set at a level that would reject about 5% of all the raw time records and each recording consisted of the average of 500 “good” sweeps (i.e. 500 test clicks).

²² As in Experiment One, all descriptions of delays and timing within waveforms are with reference to the presentation of the test click, taken to occur at time $t = 0$.

No of suppressors	Δt_1 (ms)	Δt_2 (ms)
1	-3	-
1	-2.5	-
1	-2	-
1	-1.5	-
1	-1	-
1	-0.5	-
2	-3	-2
2	-3	-1
2	-2	-1
1	0	-
1	0.5	-
1	1	-
1	2	-
1	3	-
1	4	-
1	5	-
2	2	3
2	2	4
2	2	5
2	3	4
2	3	5
2	4	5
2	-2	3
2	-2	4
2	-2	5
2	-1	3
2	-1	4
2	-1	5

Table 9.1. Values of Δt for the one or two suppressor clicks presented in Experiment Two, with respect to the presentation of the test click. For all conditions, $L_T = L_S = 60$ dB pe SPL.

A “semi-interleaved” testing protocol was again used, in which replicate pairs of *suppressor* measurements were always bracketed amongst pairs of *no-suppressor* measurements, in order once again to maximise sensitivity to changes in CEOAE amplitude. Thus, for the 28 different *suppressor* conditions in Table 6.1, 85 CEOAE waveforms were recorded as described above. The test parameters for the 85 successive recordings within a measurement sequence were stored in an initialisation file and automatically retrieved and set by the system software as necessary. The waveforms recorded were monitored visually during testing and stored to disk for subsequent analyses.

With the exception of the middle-ear tests, all the measurements in Experiment Two were conducted with the subject within the sound-isolated booth, with visual contact with the tester and visual feedback of CEOAE recordings as in Experiment One.

Execution of the various procedures in Experiment Two took a total of approximately two and a half hours for each subject. These were always conducted within the same day, with the exception of one subject, in whose case testing was spread over two successive days. For that subject, administration of the questionnaire section pertinent to the day of testing, otoscopy and tympanometry were conducted on both days.

10. Results – Experiment Two²³

All results presented in this chapter are based upon the quantification of CEOAE amplitudes in the 6-16 ms waveform time segment. This represents essentially a whole-waveform CEOAE measure,²⁴ and was used in preference to amplitude measures within more restricted time segments for several reasons. Firstly, the measurements of Picton *et al.* (1993) (and the corresponding measurements of Kemp and Chum (1980)) upon which these authors' hypothesis of an accumulation of single-click suppression was based, were whole-waveform measures. Furthermore, if such an accumulation of suppression holds generally within restricted time segments, it should also hold for wider segments and the whole CEOAE waveform. However, the converse may not be true: it is possible that if the effect of each suppressor click is in a different time segment, an accumulation of suppression may apply when these time segments are combined in measuring CEOAE amplitude, but not for any one segment in isolation.

²³ Aspects of these data were presented at the British Society of Audiology Short Papers Meeting on Experimental Studies in Hearing and Deafness, University of Cambridge, 22-23 September 1996, and published as a short communication (Kapadia *et al.*, 1997).

²⁴ As subjects were not excluded from this experiment on the basis of CEOAE amplitudes, the very late waveform segments in some cases did not contain a large signal component. The 6-16 ms segment was therefore used for the "whole-waveform" measures here, rather than the 6-24 ms segment as in Experiment One.

10.1 General results for single suppressor clicks

The solid line in Figure 10.1 shows the mean suppression curve (± 1 SD) for all 14 subjects as a function of Δt , for *single* suppressor clicks only. Also reproduced in the figure for reference (dashed line) is the corresponding mean curve from Experiment One (Figure 7.4) for the same click levels ($L_T = L_S = 60$ dB pe SPL).

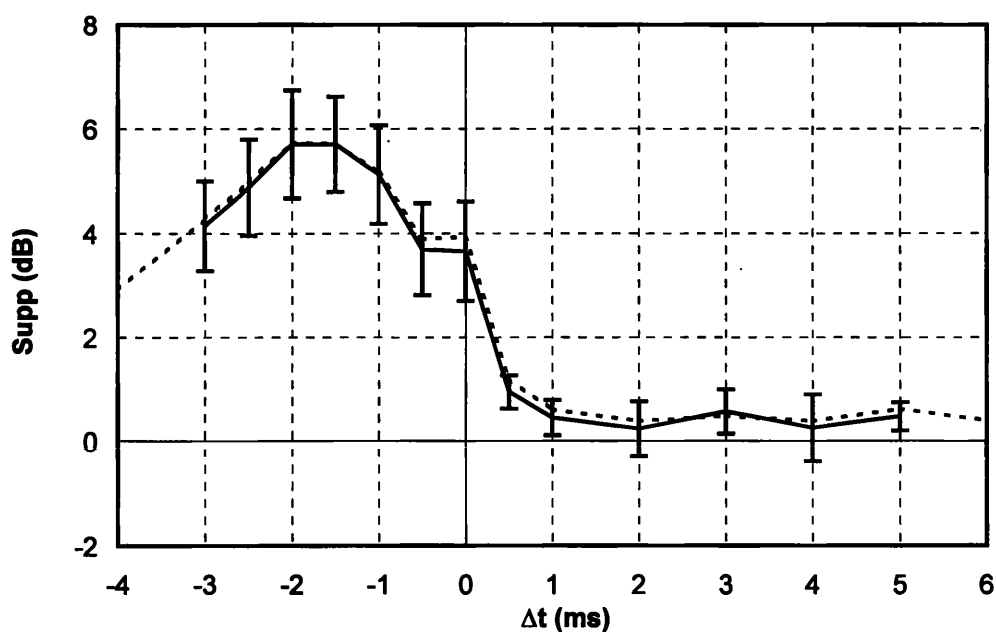


Figure 10.1. Solid line – mean measured CEOAE suppression (± 1 SD) across all 14 ears versus Δt , for single suppressor click measurements only. Dashed line – corresponding mean curve from Experiment One for the same click levels (SD not shown).

Figure 10.1 demonstrates that over the (narrower) range of Δt values used in this experiment, the amount and pattern of suppression for single suppressor clicks is

virtually identical to that obtained in the more detailed measurements of Experiment One. Once again, the general features of the mean curve shown, including that of the peak of suppression occurring at a Δt value clearly less than zero, were closely followed in the individual curves for each of the subjects tested. (It should be noted, however that 6 of the 14 subjects used in Experiment Two were also used in Experiment One.) This confirms to a degree the generality and repeatability of the results obtained for single suppressor clicks, and further suggests that a similar generality may be assumed for the results on accumulation of suppression presented below.

10.2 Accumulation of leading suppressors

In hypothesising that the suppression due to single suppressor clicks might accumulate when multiple suppressors are presented, Picton *et al.* (1993) did not specify the exact nature that such accumulation might take. However, the hypothesis might be interpreted in the most general and assumption-free form as follows:

Let the suppression in dB due to suppressor S_1 be denoted as $supp_1$, and suppression due to suppressor S_2 be denoted $supp_2$. Then an accumulation of suppression when both suppressors are applied together implies that the net suppression

$$supp_{(1,2)} > \max(supp_1, supp_2) \quad \dots \text{Eqn. 10.1}$$

Note that this formulation of the accumulation hypothesis does not necessitate an exact additivity (in terms of dB) of suppression. Thus, for example if a pair of suppressors

individually yield 2 and 3 dB of suppression, the net suppression when both are applied need not be 5 dB, but merely greater than 3 dB.

Figure 10.2 to Figure 10.4 present the results on accumulation of suppression due to leading suppressors in a manner that permits a ready examination of the accumulation hypothesis as stated above. Each of these figures shows the suppression measured for each of the 14 subjects, and the mean across subjects, as a clustered column graph representing a particular pair-wise combination of suppressor clicks. Three columns are plotted for each subject, showing respectively the suppression due to the first suppressor alone, the second suppressor alone and for both the suppressors presented in combination.²⁵

²⁵ For the sake of clarity in these and following discussions on pairs of suppressors, the term “first” or “second” suppressor is used respectively to refer to the suppressor that either leads or follows the other.

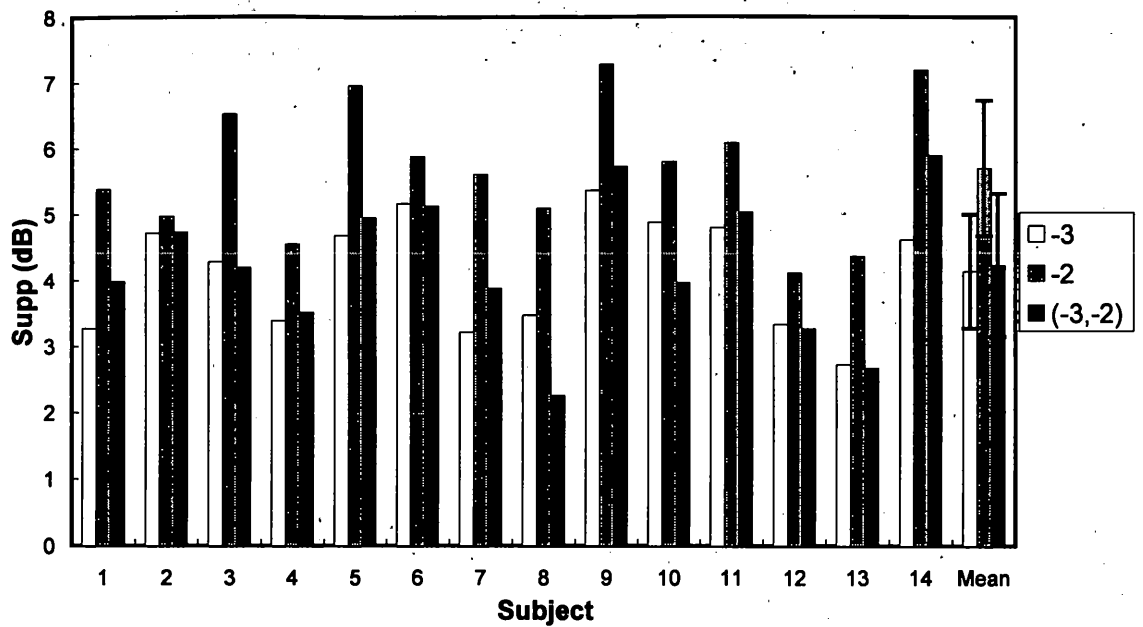


Figure 10.2. Suppression due to a single suppressor at $\Delta t = -3$, a single suppressor at $\Delta t = -2$ and a *pair* of suppressors at -3 and -2 ms. Data are shown for each of the 14 subjects and for the mean (± 1 SD) across all subjects.

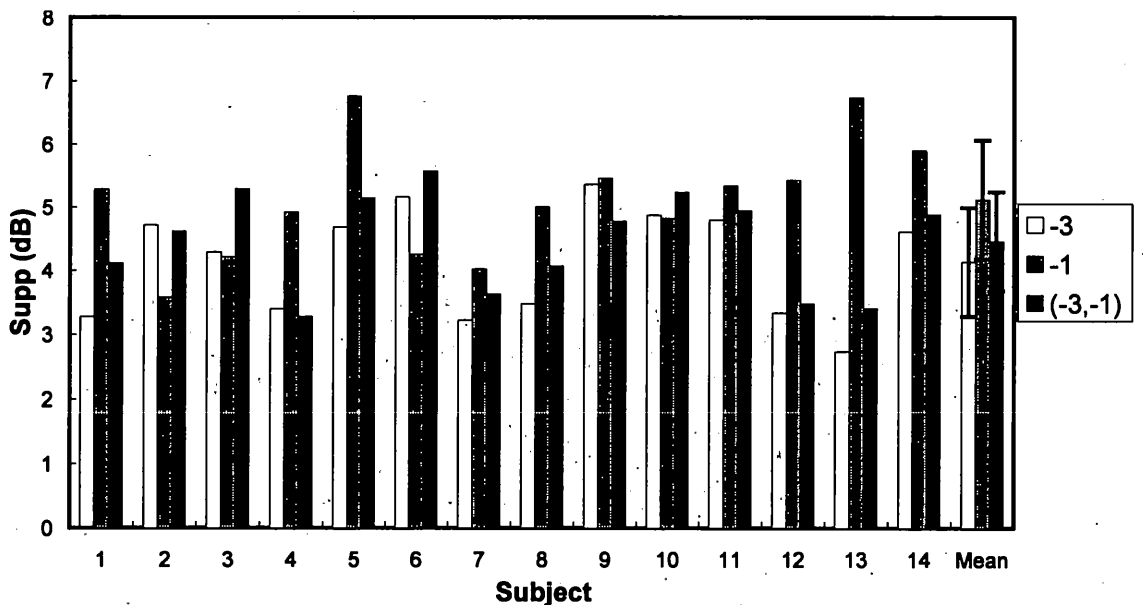


Figure 10.3. Suppression due to a single suppressor at $\Delta t = -3$, a single suppressor at $\Delta t = -1$ and a *pair* of suppressors at -3 and -1 ms. Data are shown for each of the 14 subjects and for the mean (± 1 SD) across all subjects.

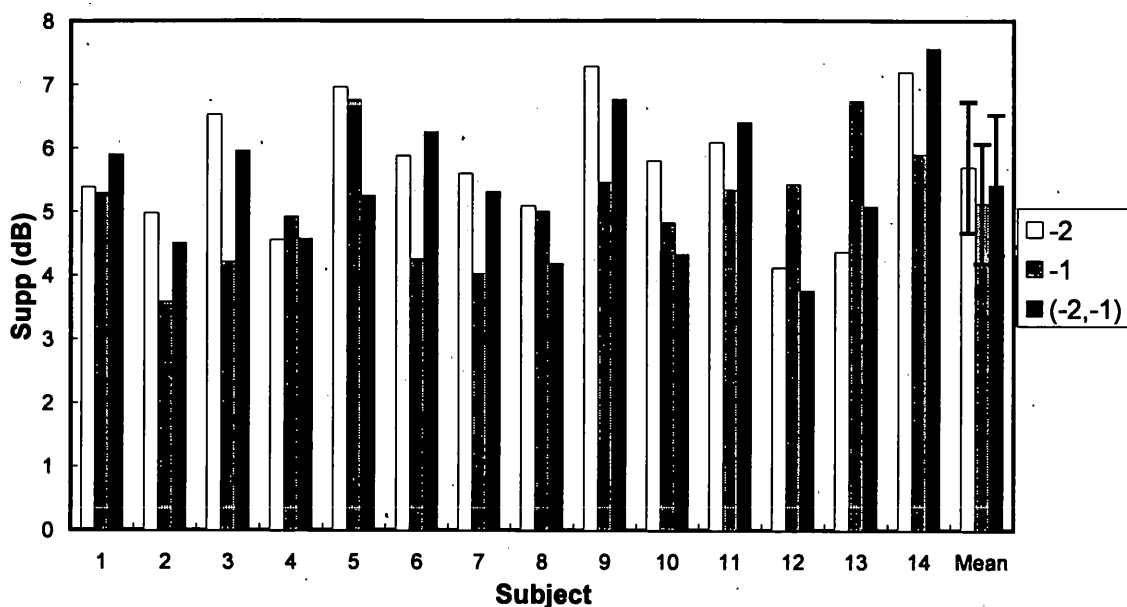


Figure 10.4. Suppression due to a single suppressor at $\Delta t = -2$, a single suppressor at $\Delta t = -1$ and a pair of suppressors at -2 and -1 ms. Data are shown for each of the 14 subjects and for the mean (± 1 SD) across all subjects.

Figure 10.2 through Figure 10.4 show clearly that the hypothesis of a simple accumulation of single-click suppression as described above does not apply to any of the three pair-wise combinations of leading suppressor clicks examined here.

In Figure 10.2, suppressor clicks at $\Delta t = -3$ and -2 ms are examined. Consistent with the mean data shown in Figure 10.1, suppression due to a single suppressor at -2 ms is always greater than that due to one at -3 ms. However, when both suppressors are presented in combination, the net suppression is always *less* than that due to the suppressor at -2 ms alone. Furthermore, in 4 of the 14 cases (most notably for subjects 8 and 10), the net suppression is less than that due to *either* of the suppressors

individually. Statistical tests of these effects and those shown in the subsequent two figures are described below.

Figure 10.3 (suppressors at $\Delta t = -3$ and -1 ms) shows a similar pattern of results, in that the suppression due to both the suppressors in combination is *not* generally greater than that due to the more effective suppressor individually – although this is observed in 3 of the 14 subjects (subjects 3, 6 and 10).

Similarly, in Figure 10.4, the suppression due to both suppressors is generally less than that due to the more effective of the individual suppressors, although the (converse) hypothesised pattern of accumulation is observed in four subjects – subjects 1, 6, 11 and 14.

Table 10.1 summarises the above data in terms of the number of cases for which the net suppression is greater than the maximum suppression for the two suppressors individually (the hypothesised relationship described by Equation 10.1) and less than this maximum, for each of the three figures plotted above.

A Wilcoxon signed-rank test for two related samples confirms that in each of the three above sets of data for pairs of leading suppressors, the net suppression is not significantly greater than the maximum single-suppressor suppression. (In fact, in all three cases the net suppression is significantly *less* than the maximum single-suppressor suppression, with a single-tailed $p < 0.05$).

Δt (ms)	Number of cases	Number of cases	Total
	$supp_{1,2} > \max(supp_1, supp_2)$	$supp_{1,2} < \max(supp_1, supp_2)$	
(-3, -2)	0	14	14
(-3, -1)	3	11	14
(-2, -1)	4	10	14

Table 10.1. Number of cases for which the net suppression is greater than the maximum suppression for the corresponding suppressors individually (as hypothesised) and less than this maximum, for each of the three conditions of pairs of leading suppressors.

The results presented above indicate that the suppression due to individual leading suppressor clicks does not simply accumulate when pairs of such suppressors are used. Rather, a more complex interaction between the suppressors and the test click would appear to be involved in generating the net suppression observed. This is further discussed in the general discussion of the results of Experiment Two (Chapter 11).

10.3 Accumulation of following suppressors

Although the hypothesis of Picton *et al.* (1993) of an accumulation of single-suppressor suppression leading to a quantitatively greater magnitude of MLS rate suppression was formulated primarily for suppression due to leading suppressor clicks, it may also be instructive to examine to what degree such accumulation applies to a pair of following suppressors.

Figure 10.5 to Figure 10.10 plot the data for pairs of following suppressors for all 14 subjects, following the format of Figure 10.2 to Figure 10.4 presented previously for pairs of leading suppressor clicks.

Ignoring cases where one or other of the individual suppressors leads to an *enhancement* of the CEOAE (negative value of suppression), it is clear from the figures that there is once again no general trend for the net suppression to exceed the greater of the individual suppression values. In some instances (e.g. subject 7 in Figure 10.6, subject 14 in Figure 10.8) an enhancement is observed when both suppressors are presented in combination, despite no appreciable enhancement due to either suppressor individually.

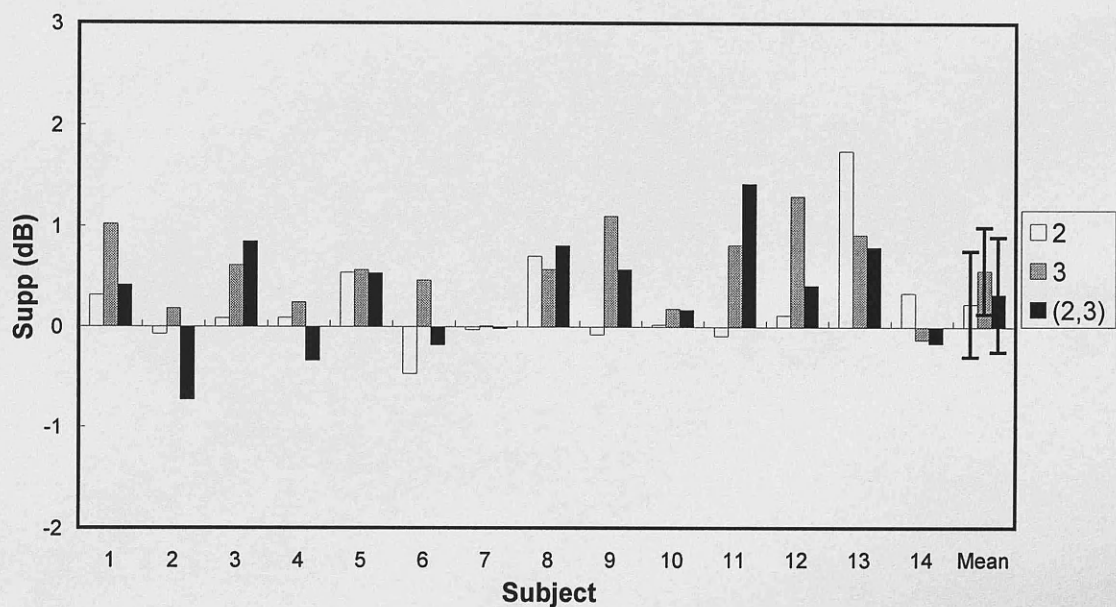


Figure 10.5. Suppression due to a single suppressor at $\Delta t = 2$, a single suppressor at $\Delta t = 3$ and a pair of suppressors at 2 and 3 ms. Data are shown for each of the 14 subjects and for the mean (± 1 SD) across all subjects.

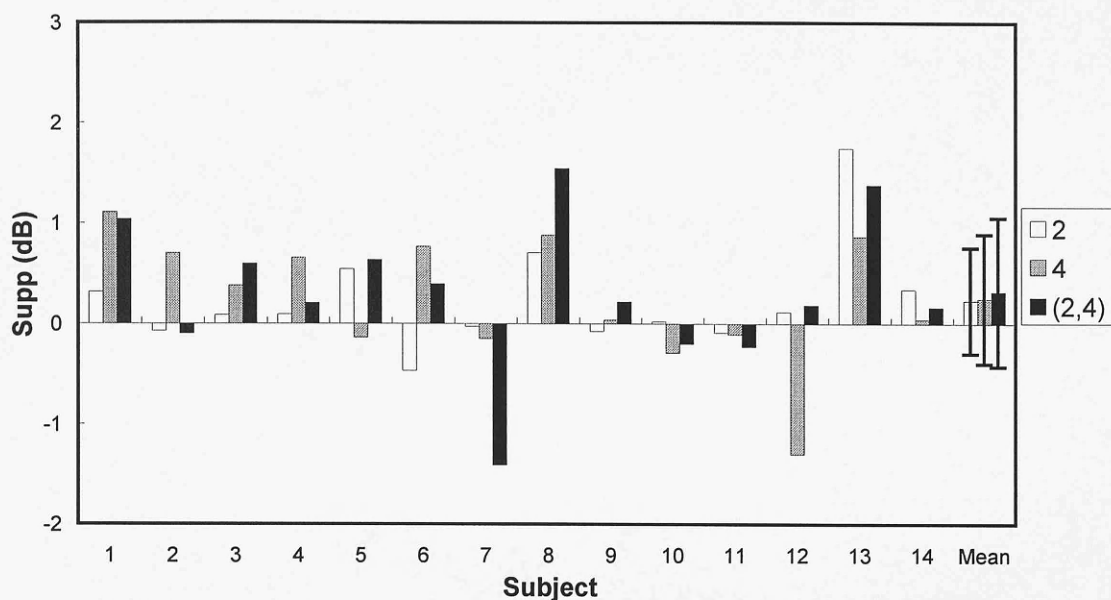


Figure 10.6. Suppression due to a single suppressor at $\Delta t = 2$, a single suppressor at $\Delta t = 4$ and a pair of suppressors at 2 and 4 ms. Data are shown for each of the 14 subjects and for the mean (± 1 SD) across all subjects.

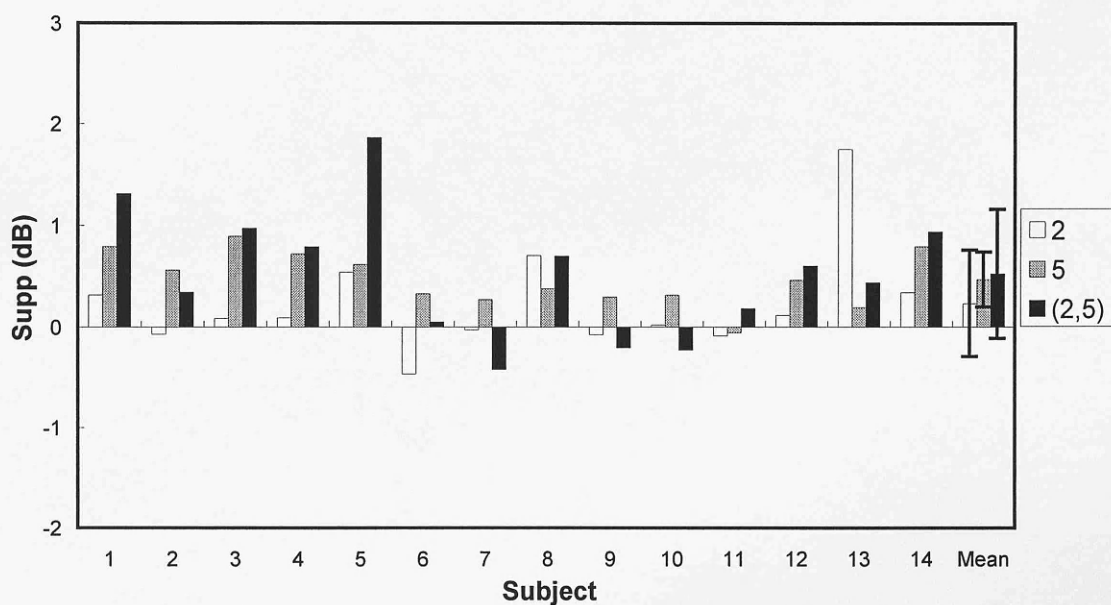


Figure 10.7. Suppression due to a single suppressor at $\Delta t = 2$, a single suppressor at $\Delta t = 5$ and a pair of suppressors at 2 and 5 ms. Data are shown for each of the 14 subjects and for the mean (± 1 SD) across all subjects.

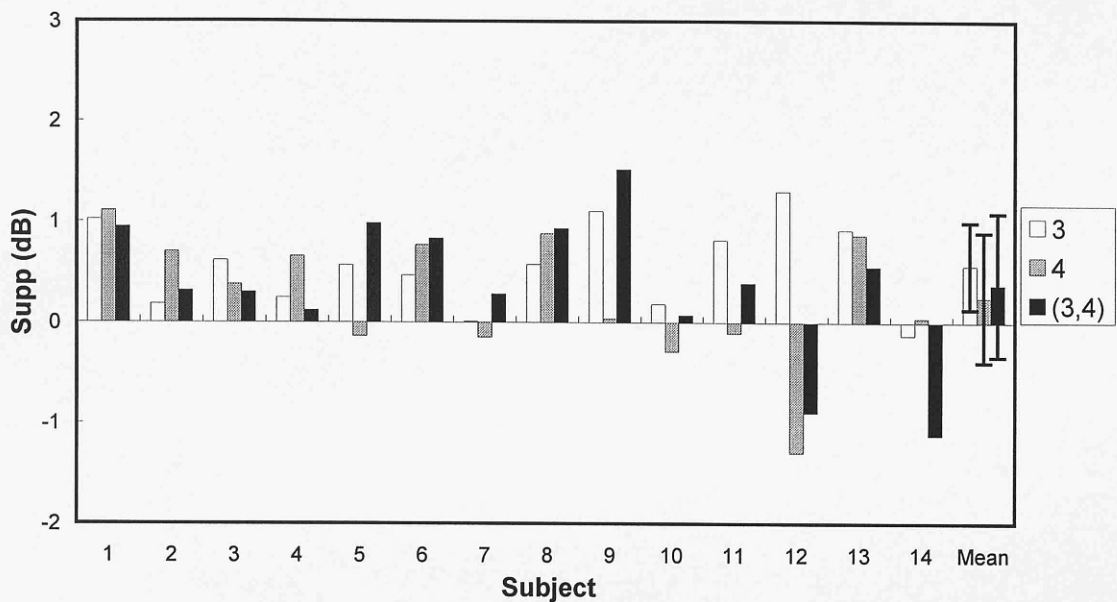


Figure 10.8. Suppression due to a single suppressor at $\Delta t = 3$, a single suppressor at $\Delta t = 4$ and a pair of suppressors at 3 and 4 ms. Data are shown for each of the 14 subjects and for the mean (± 1 SD) across all subjects.

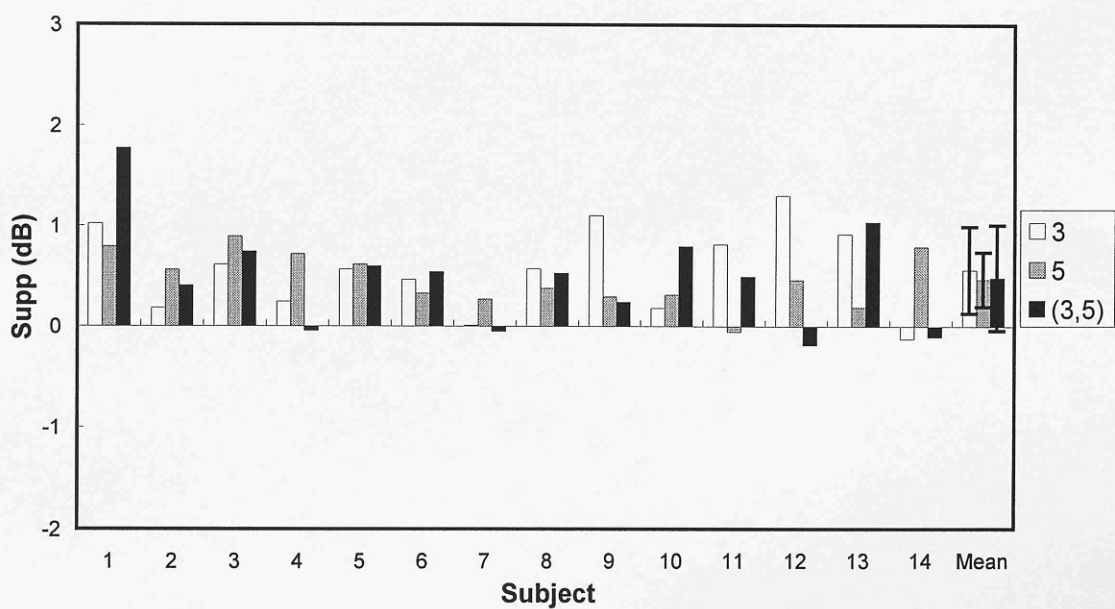


Figure 10.9. Suppression due to a single suppressor at $\Delta t = 3$, a single suppressor at $\Delta t = 5$ and a pair of suppressors at 3 and 5 ms. Data are shown for each of the 14 subjects and for the mean (± 1 SD) across all subjects.

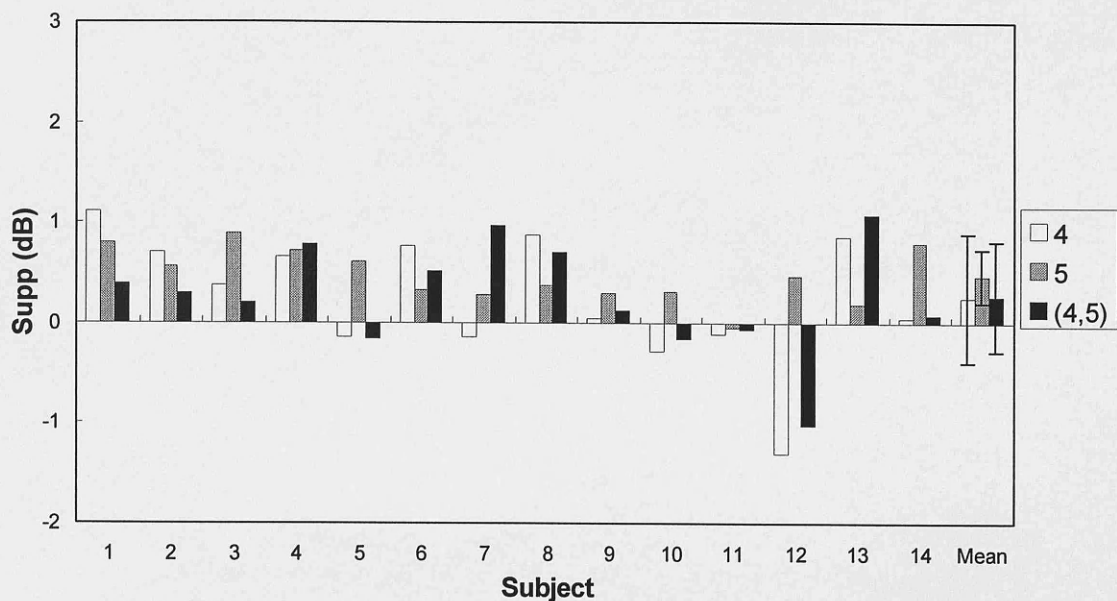


Figure 10.10. Suppression due to a single suppressor at $\Delta t = 4$, a single suppressor at $\Delta t = 5$ and a pair of suppressors at 4 and 5 ms. Data are shown for each of the 14 subjects and for the mean (± 1 SD) across all subjects.

Following the format of Table 10.1, Table 10.2 indicates the number of cases for which the net suppression is greater than and is less than the maximum suppression for the two suppressors individually, this time for the pairs of following suppressors tested. However, for this table and the subsequent statistical tests, cases in which appreciable *enhancement* occurred in either single-suppressor condition (suppression ≤ -0.5 dB) were first excluded from the analysis. This is reflected in the total number of cases in the table being less than 14 for some conditions.

Δt (ms)	Number of cases	Number of cases	Total
	$supp_{1,2} > \max(supp_1, supp_2)$	$supp_{1,2} < \max(supp_1, supp_2)$	
(2, 3)	3	11	14
(2, 4)	4	9	13
(2, 5)	7	7	14
(3, 4)	5	8	13
(3, 5)	4	10	14
(4, 5)	3	10	13

Table 10.2. Number of cases for which the net suppression is greater than the maximum suppression for the corresponding suppressors individually (as hypothesised) and less than this maximum, for pairs of following suppressors.

A Wilcoxon signed-rank test confirms that in each of the six conditions for pairs of following suppressors, the net suppression is *not* significantly greater than the maximum single-suppressor suppression. In two cases (suppressors at 2 and 3 ms and at 4 and 5 ms) the net suppression is significantly *less* than the maximum single-suppressor suppression (single-tailed $p < 0.05$). (In the remaining four cases there is no significant difference between the suppression values under consideration.)

10.4 Accumulation of mixed suppressors

A following suppressor click produces little suppression in comparison with a leading suppressor (see Figure 10.1, Figure 7.4 and Experiment One). However it may be expected that a simple accumulation of suppression would be most likely with one suppressor leading and one following the test click, rather than with both suppressors leading or both following the test click. This is because in the condition of mixed suppressors (particularly for the Δt values used in this experiment) the two suppressor clicks are themselves maximally separated. Assuming that inter-suppressor nonlinear effects reduce with increasing separation (following the pattern of single-suppressor suppression), little suppressor-suppressor interaction may be expected in this condition. Furthermore, as discussed in Experiment One (Chapter 8), the mechanisms of click suppression for leading and following suppressors are likely to be different: a simple accumulation of the effects of the two suppressors may also be more likely if the underlying mechanisms are independent of each other.

Figure 10.11 through to Figure 10.16 present the results of Experiment Two for pairs of suppressors with one suppressor click leading and one following the test click. The format used is the same as that of previous figures in this chapter (e.g. Figure 10.2), which permits a ready assessment of the accumulation hypothesis as described in Section 10.2. For mixed suppressors, the suppression due to the leading suppressor is always greater than that due to the following one: hence the test of the accumulation hypothesis reduces to a test of whether the net suppression tends to be greater than the suppression for the leading suppressor alone.

Once again ignoring cases in which CEOAE enhancements (negative values of suppression) occurred, Figure 10.11 through to Figure 10.16 indicate a substantially greater tendency for an accumulation of suppression for mixed suppressors than for either both suppressors leading or both following the test click. For example, an increase in net suppression (as hypothesised) is seen in as many as 11 of the 14 cases in Figure 10.14 and Figure 10.16. However, this applies to only seven cases in Figure 10.11 and in six in Figure 10.12.

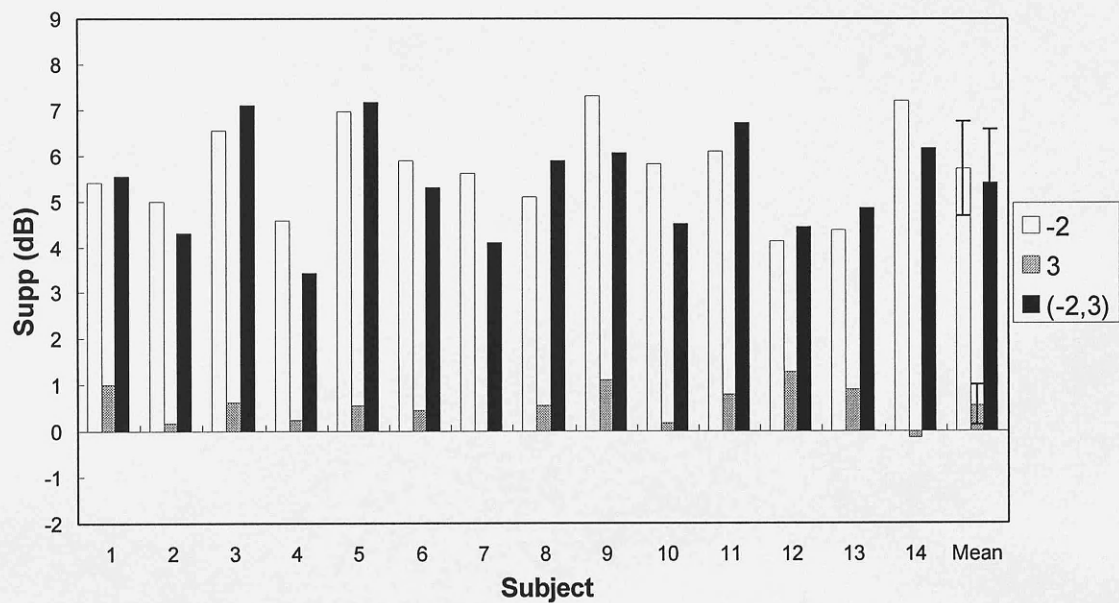


Figure 10.11. Suppression due to a single suppressor at $\Delta t = -2$, a single suppressor at $\Delta t = 3$ and a pair of suppressors at -2 and 3 ms. Data are shown for each of the 14 subjects and for the mean (± 1 SD) across all subjects.

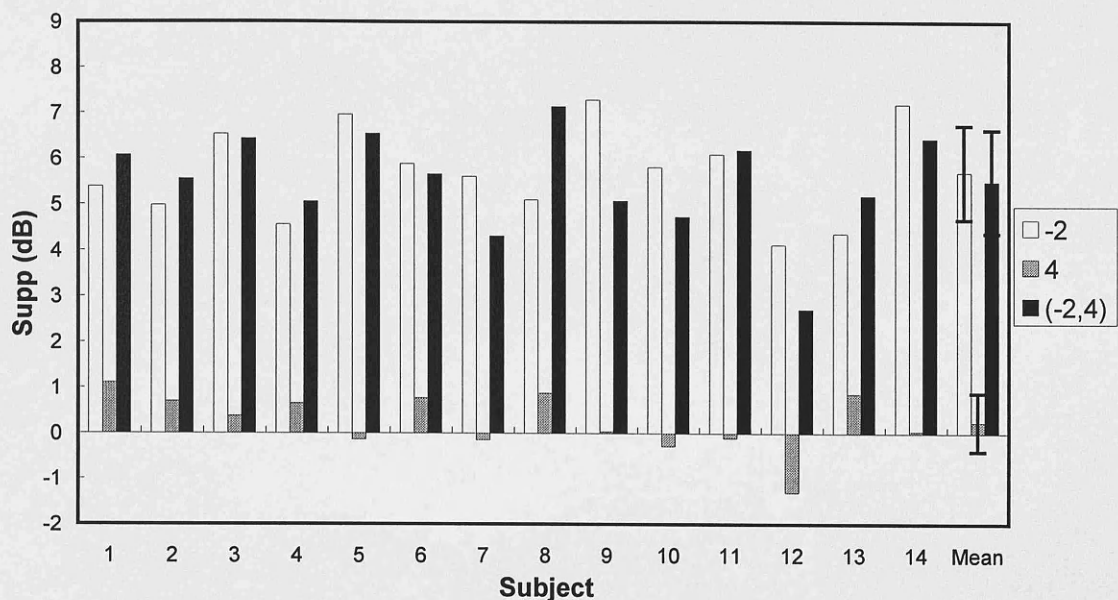


Figure 10.12. Suppression due to a single suppressor at $\Delta t = -2$, a single suppressor at $\Delta t = 4$ and a pair of suppressors at -2 and 4 ms. Data are shown for each of the 14 subjects and for the mean (± 1 SD) across all subjects.

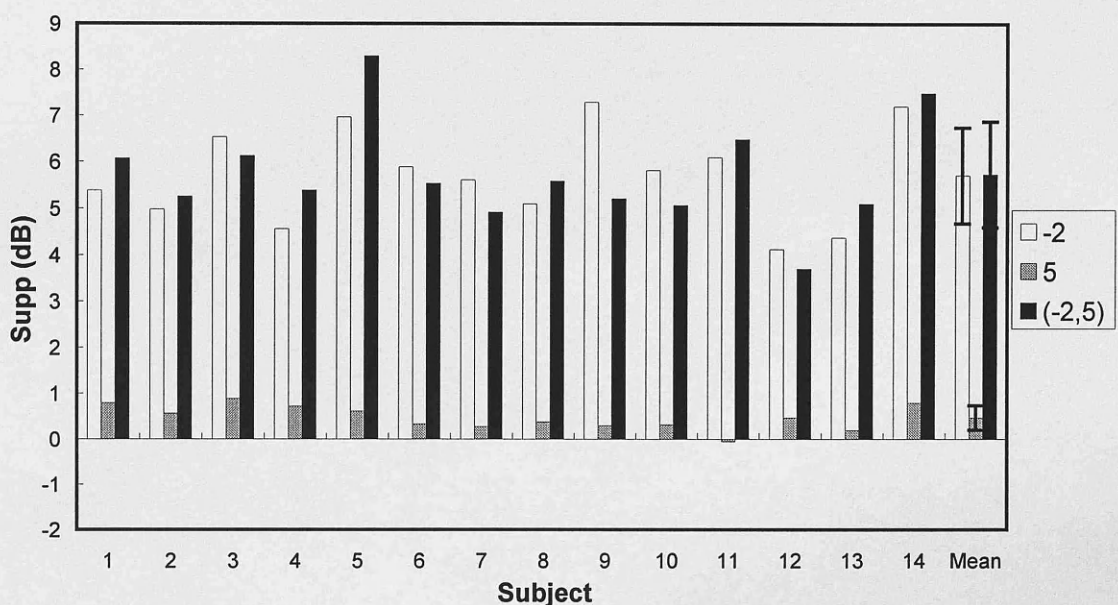


Figure 10.13. Suppression due to a single suppressor at $\Delta t = -2$, a single suppressor at $\Delta t = 5$ and a pair of suppressors at -2 and 5 ms. Data are shown for each of the 14 subjects and for the mean (± 1 SD) across all subjects.

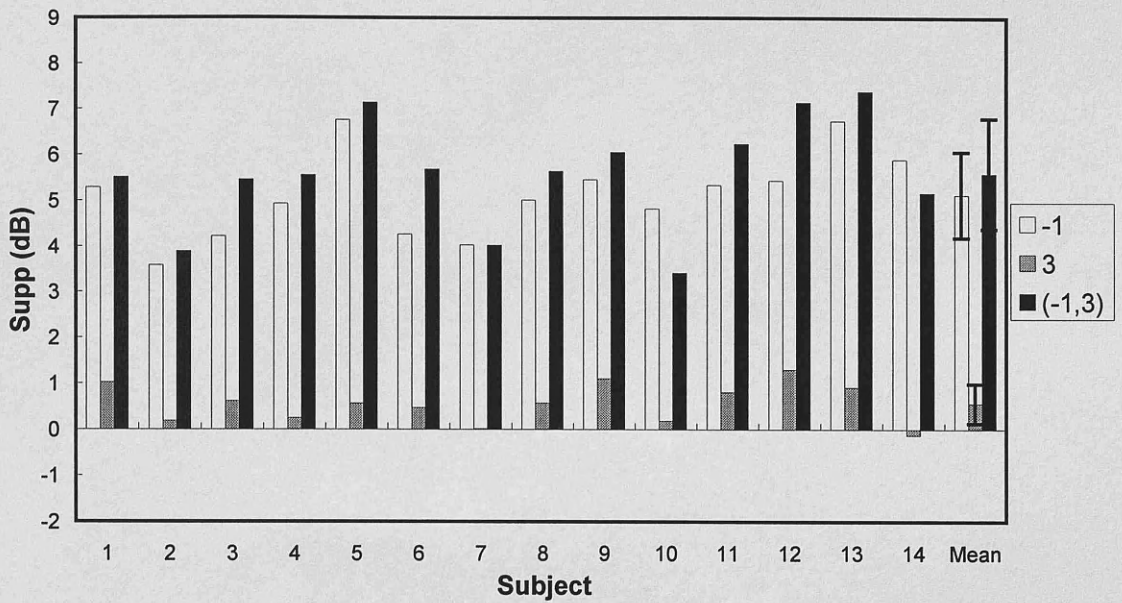


Figure 10.14. Suppression due to a single suppressor at $\Delta t = -1$, a single suppressor at $\Delta t = 3$ and a pair of suppressors at -1 and 3 ms. Data are shown for each of the 14 subjects and for the mean (± 1 SD) across all subjects.

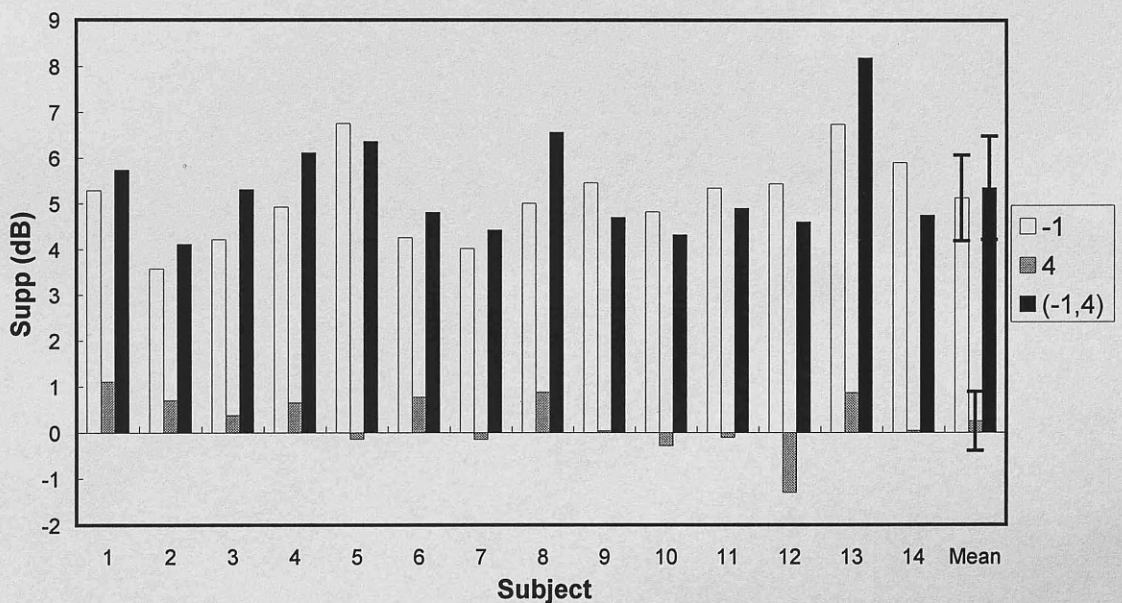


Figure 10.15. Suppression due to a single suppressor at $\Delta t = -1$, a single suppressor at $\Delta t = 4$ and a pair of suppressors at -1 and 4 ms. Data are shown for each of the 14 subjects and for the mean (± 1 SD) across all subjects.

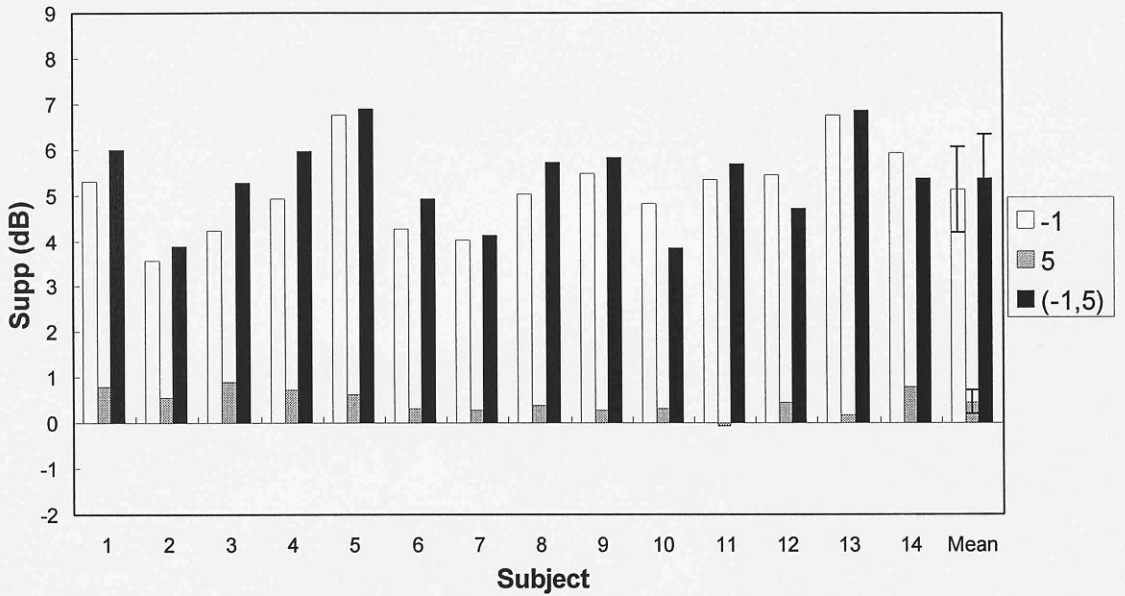


Figure 10.16. Suppression due to a single suppressor at $\Delta t = -1$, a single suppressor at $\Delta t = 5$ and a pair of suppressors at -1 and 5 ms. Data are shown for each of the 14 subjects and for the mean (± 1 SD) across all subjects.

Table 10.3 lists in full the number of cases for which the net suppression is greater than and is less than the maximum suppression for the two suppressors individually (i.e. for the suppression due to the leading suppressor alone), for the pairs of mixed suppressors used. As in Section 10.3, cases in which enhancement ≥ 0.5 dB occurred in either single-suppressor condition (suppression ≤ -0.5 dB) are excluded from the table and the subsequent statistical tests.

Δt (ms)	Number of cases	Number of cases	Total
	$supp_{1,2} > \max(supp_1, supp_2)$	$supp_{1,2} < \max(supp_1, supp_2)$	
(-2, 3)	7	7	14
(-2, 4)	6	7	13
(-2, 5)	8	6	14
(-1, 3)	11	3	14
(-1, 4)	8	5	13
(-1, 5)	11	3	14

Table 10.3. Number of cases for which the net suppression is greater than the maximum suppression for the corresponding suppressors individually (as hypothesised) and less than this maximum, for pairs of mixed suppressors (one leading and one following the test click).

A Wilcoxon signed-rank test conducted for each of these six conditions of pairs of mixed suppressors indicates that the increase in net suppression over that for the leading suppressor alone is statistically significant for the condition of $\Delta t = -1$ and 3 ms (single-tailed $p < 0.05$). For three other conditions ($\Delta t = -2$ and 5 ms, -1 and 4 ms, and -1 and 5 ms), although there is a tendency for such an accumulation (as evident in Table 10.3), the effect is not statistically significant.

11. Discussion – Experiment Two

Experiment Two aimed to determine whether the suppression due to multiple suppressor clicks accumulated in a simple, additive manner as had been postulated by Picton *et al.* (1993). These authors had suggested that such an accumulation of suppression could account for the shortfall between the maximum suppression for a single leading suppressor reported by Kemp and Chum (1980) and the suppression observed by themselves in recording CEOAEs at high click rates using the MLS technique. In keeping with these arguments, and the observation from the present study and earlier reported data (Kemp and Chum, 1980; Lina-Granade and Collet, 1995) that leading suppressor clicks are far more effective than following ones over the entire CEOAE waveform, the accumulation of suppression due to leading suppressors was of main interest here.

11.1 Leading suppressors

The results reported in the previous chapter (Section 10.2), in which suppression due to a single and to pairs of leading suppressors is compared within the same subjects, contradict the above hypothesis of a simple accumulation of suppression. A simple accumulation of suppression would imply that the net suppression due to both suppressors would *exceed* that due to either suppressor individually: this is not found to apply generally for any of the pairs of leading suppressors used. It is in fact found that the net suppression is statistically significantly less than that due to the more effective suppressor individually, for all three combinations of leading suppressors used here.

It therefore follows that the suppression due to individual leading suppressor clicks does not simply accumulate when pairs of such suppressors are used. Rather, a more complex process must be invoked, involving for example, nonlinear interactions between the suppressors themselves, or changes in the nonlinear interactions between a suppressor and a test click (and their CEOAEs) in the presence of a second suppressor.

Any changes in suppressor-test nonlinear interactions as above would be difficult to predict from the present data. However, it is possible to develop the model of a simple accumulation of suppression further, by assuming that such suppressor-test interactions are unchanged, but by taking into account possible suppressor-suppressor interactions. It may be assumed that the primary effect of such interactions would be to *reduce* the net suppression generated. Such a reduction or “release from suppression” has been reported by Rabinowitz and Widin (1984) in examining the effects of multiple pure-tone suppressors on spontaneous OAEs. It would also be consistent with the basic finding above of less net suppression than that expected from a simple accumulation of effects.

11.1.1 Effects of inter-suppressor interactions

In Chapter 8 it was hypothesised that the mechanism of suppression for a leading suppressor click might be related to a disturbance of the CEOAE generator elements from their resting state, prior to the excitation by the test click. It may be argued that the suppressive power of the second (“following”) suppressor in a pair of suppressor clicks would be similarly reduced by the first (“leading”) suppressor. A comparatively minor effect on the first suppressor due to the presence of the second one may be expected, due

to the correspondingly small effect on a test click of a single closely-following suppressor as compared to a single closely-leading one at the same absolute value of Δt (see Figure 10.1).

It is not possible to predict the amount by which the suppression due to the second suppressor in a pair would be reduced by the presence of the first. However, it may be hypothesised that this reduction in suppressive power for a given *inter-suppressor* interval would be related to the amount of suppression at the corresponding value of Δt in a *single-suppressor* experiment. Thus for example, the reduction in suppressive power of a suppressor at $\Delta t = -2$ ms, due to the prior presentation of a suppressor at $\Delta t = -3$ ms, may be expected to be related to the amount of suppression due to a single suppressor at $\Delta t = -1$ ms. (In a special case of this broad hypothesis the above reduction in suppressive power may be *equal* to the amount of suppression at $\Delta t = -1$ ms, but this exact equivalence of single-suppressor suppression on the one hand and paired-suppressor reduction in suppression on the other may not be expected in a nonlinear system.)²⁶

It was therefore assumed that the net suppression in dB generated by a pair of leading suppressor clicks in the *absence* of any interactions between the two suppressors would be equal to the sum of the suppression in dB due to each suppressor individually. However, the presence of inter-suppressor interactions as hypothesised above would

²⁶ Note that, in contrast to the situation for suppressor-test interactions, the issue of a polarity-sensitivity of suppressor-suppressor interactions does not arise here, as all suppressor clicks were of the same polarity in the test paradigm used.

lead to a “shortfall” in the net suppression actually measured. Thus, following the terminology of the previous chapter (Equation 10.1),

$$supp_{(1,2)} = supp_1 + supp_2 - \text{shortfall} \quad \dots \text{Eqn. 11.1}$$

This shortfall is equal to the “reduction in suppressive power” in dB of the second suppressor due to the presentation of the first in the hypothesis described above. As the three suppression values in Equation 11.1 above were determined by measurement, the shortfall value in the equation was calculated for each subject and each combination of suppressors used. These values of shortfall were then plotted against the corresponding value of single-suppressor suppression (for a Δt value equal to the inter-suppressor interval), to test for a relationship as hypothesised above. Under this hypothesis, and for the shortfall as defined above, a greater amount of suppression at a given value of Δt in the single-suppressor measurement should result in a greater shortfall in the net suppression for a pair of suppressor clicks separated by Δt .

Figure 11.1 plots the values of the shortfall for a pair of suppressors at $\Delta t = -3$ and -2 ms versus the single-suppressor suppression at $\Delta t = -1$ ms across all 14 subjects. It is clear from the figure that there is no relationship between the variables, as further confirmed by a non-significant Spearman correlation coefficient.

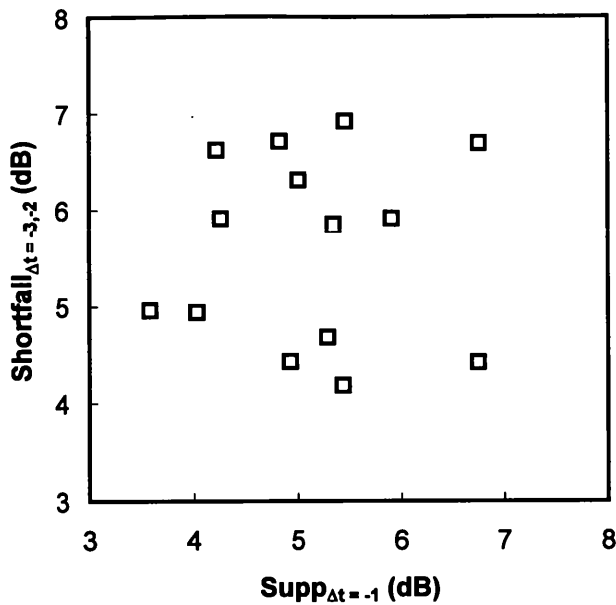


Figure 11.1. Shortfall in net suppression (calculated using Equation 11.1) for a pair of suppressors at $\Delta t = -3$ and -2 ms versus suppression due to a single suppressor at $\Delta t = -1$ ms for all 14 subjects tested in Experiment Two.

Figure 11.2 plots the corresponding data for pairs of leading suppressor clicks at $\Delta t = -3$ and -1 ms. It is once again seen that there is no correlation between the shortfall in net suppression and the suppression for a single suppressor at the appropriate value of Δt i.e., -2 ms. This is again confirmed by a non-significant Spearman correlation coefficient.

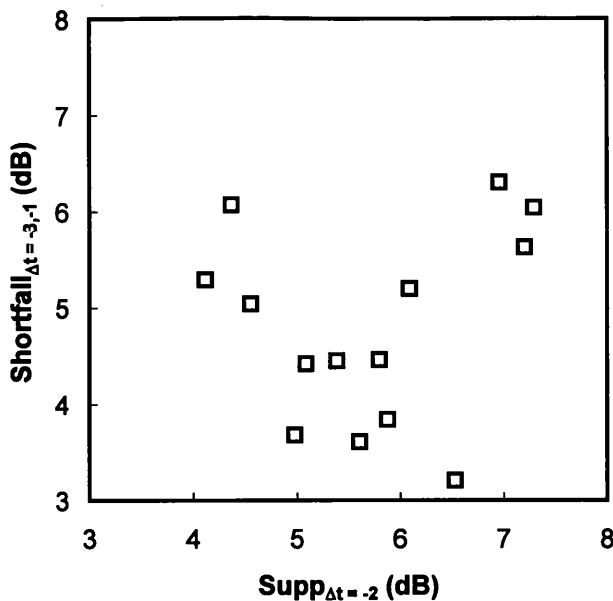


Figure 11.2. Shortfall in net suppression for a pair of suppressors at $\Delta t = -3$ and -1 ms versus suppression due to a single suppressor at $\Delta t = -2$ ms for all 14 subjects tested in Experiment Two.

Finally, Figure 11.3 plots the shortfall in net suppression for suppressors at $\Delta t = -2$ and -1 ms versus the single-suppressor suppression at $\Delta t = -1$ ms. In marked contrast to the previous two figures, a strong positive correlation between the two variables is evident here (Spearman coefficient $p < 0.01$). However, the two variables plotted in this figure are not independent, as the shortfall in net suppression in this case is calculated partly from suppression at $\Delta t = -1$ ms ($supp_2$ in Equation 11.1). The variables plotted must therefore necessarily show a positive correlation, and this condition of paired suppressors must be ignored in evaluating the hypothesised relationship.

Note that in the previous two figures, the calculation of shortfall in net suppression (for $\Delta t = -3$ and -2 and $\Delta t = -3$ and -1 ms respectively) is completely independent of the

appropriate measure of single-suppressor suppression (at $\Delta t = -1$ and $\Delta t = -2$ ms respectively), against which its correlation is tested.

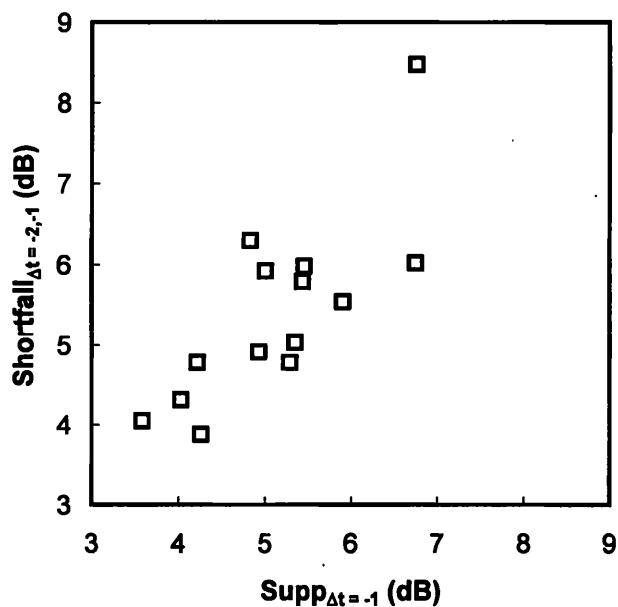


Figure 11.3. Shortfall in net suppression for a pair of suppressors at $\Delta t = -2$ and -1 ms versus suppression due to a single suppressor at $\Delta t = -1$ ms for all 14 subjects tested in Experiment Two.

The above discussions indicate that the model of generation of net suppression developed above is not adequate to explain the experimental findings. In particular, either the inter-suppressor nonlinear interactions are not simply related to (single-suppressor) suppressor-test interactions at corresponding values of Δt , or the nonlinear interactions between test and suppressor clicks (and CEOAEs) themselves are significantly altered by the presence of an additional suppressor click.

11.2 Following suppressors

Owing to the relatively small amount of suppression across the CEOAE waveform due to a following suppressor, a simple accumulation of such suppression is not likely to account for MLS rate suppression. Furthermore, the effects of following suppressors were shown in Experiment One to be somewhat more complex than those of leading suppressors – in particular showing instances of changes in CEOAE waveforms and of enhancements of amplitude. On the other hand, as following suppressors at different values of Δt could have effects upon different segments of the CEOAE waveform, some degree of accumulation of suppression may have been expected when considering the whole CEOAE waveform.

However, the results presented in Section 10.3 indicate that for the values of Δt used here, pairs of following suppressors do not yield a simple accumulation of suppression. In the formulation of the accumulation hypothesis as described by Equation 10.1, the net suppression for a pair of following suppressors was found to be not significantly different from the suppression due to the more effective suppressor for four of the paired conditions tested. For the other two conditions, the net suppression was found to be significantly *less* than that due to the more effective suppressor. As in the case of single following suppressors, relatively complex effects of pairs of following suppressors were noted, such as instances of appreciable CEOAE enhancement when both suppressors were presented jointly, though not when either suppressor was presented individually.

11.3 Mixed suppressors

The data presented in Section 10.4 indicate that in the case of mixed suppressors (one leading and one following suppressor), there is an increased tendency towards a simple accumulation of suppression (as defined), as compared to pairs of leading and pairs of following suppressors. Although the net suppression is found to be statistically significantly greater than that due to the more effective suppressor for only one of the six combinations of suppressor clicks used ($\Delta t = -1$ and 3 ms), the majority of the subjects tested showed this tendency for three other such combinations of clicks. In addition, in none of the combinations of mixed suppressor clicks was the net suppression found to be statistically significantly *less* than that due to the more effective suppressor. In contrast, this reduction in net suppression had been found for all three combinations of leading suppressor clicks and for two of the six combinations of following suppressors.

If it is indeed the case that the suppression due to mixed suppressors accumulates in the simple manner as outlined above, then it may make a significant contribution towards accounting for the shortfall between single-click suppression and MLS rate suppression, despite the relatively small net increases due to the following suppressors (which reflects the small amount of suppression due to such suppressors individually). It should be noted that the data from the present study and from other reports published subsequent to that of Picton *et al.* (1993) (e.g. Lina-Granade and Collet, 1995) indicate a far greater magnitude of suppression due to a single leading suppressor than that indicated in the data of Kemp and Chum (1980), upon which the arguments of Picton *et al.* (1993) were based. As described in Chapter 2, subject to certain assumptions, for

equilevel test and suppressor clicks and $\Delta t = -2$ ms, an effective suppression of approximately 3 dB can be derived from the data of Kemp and Chum (1980). This compares with a mean suppression value approaching 6 dB at the same value of Δt for the single-suppressor data of the present study (Figure 10.1).²⁷

However, due to the small size of the increases in suppression involved and the variability in suppression across the subjects (as indicated in the column graphs in Section 10.4), more detailed measurements using mixed suppressors, involving larger numbers of subjects, are required in order to confirm the apparent tendency for a simple accumulation in these data. The use of greater numbers of suppressor clicks and comparisons with MLS rate suppression data obtained in the same subjects would also be useful in assessing to what degree the accumulation of click suppression may account for the greater magnitude of rate suppression.

In considering the shortfall between click suppression and MLS rate suppression, it should be noted that MLS-recorded CEOAEs typically benefit from a far lower noise floor, due to the greater amount of averaging that can be achieved using that technique. For example, at an average click rate of 2500 click/s the responses to 25,000 clicks may be recorded in 10 seconds. By comparison, a maximum of about 400 averages would be

²⁷ The magnitude of rate suppression at high MLS click rates has also increased as higher click rates have become possible. Unpublished data obtained by the author using the same test equipment as used in this project indicate MLS rate suppression values of as much as 10 dB in some subjects. There therefore remains a shortfall to be addressed between single-suppressor click suppression and MLS rate suppression.

recorded in the same time using the click suppression techniques and recording parameters of the present study. As the level of (random) noise theoretically decreases by the square root of the number of averages, the noise floor for the MLS recording would be lower by as much as 15 dB in this example.

Note, however, that the above theoretical difference in noise level may overestimate the difference obtained in practice as:

- (i) The (biological) noise encountered in practice tends to be non-stationary and its level typically does not reduce by the square root of the number of averages.
- (ii) The recording time used in each type of study would rarely be the same – MLS recordings generally take advantage of the technique in order to shorten the recording time as compared to conventional measurements.

Nevertheless, if the suppression values are limited by the recording noise floor (or “suppression ceilings”) as was sometimes found to be the case in the data of Experiment One, then any lowering of noise floor in an MLS recording would result in a greater amount of suppression measured in that case.

The degree to which such a reduction of the noise floor might contribute to the apparently greater amount of rate suppression could be assessed by ensuring that an equivalent degree of averaging is used in comparing the two forms of suppression (ideally again in the same subjects). Careful quantification of the noise floors (or

equivalently the suppression ceilings) in the recordings in each case would also be useful in this regard.

Finally, it is noted that the $\Delta t = 0$ (synchronous suppressor) condition was not included in any of the paired-suppressor measurements in the present study. This was because it does not represent a condition that can arise in the high click-rate CEOAE measurements that primarily motivated these investigations. However, the inclusion of this condition in any future studies of the accumulation of click suppression between mixed suppressors may well have some basic scientific value. As discussed previously (Chapter 4), suppression in the special case of a synchronous suppressor is necessarily derived from the nonlinearity of the CEOAE level function. Furthermore, Experiment One of the present study indicated that while suppression due to a leading suppressor is not directly related to level function nonlinearity, that due to a following suppressor may well be. It may therefore be of interest to compare the additivity of suppression between a leading and a synchronous suppressor on the one hand, and a following and a synchronous suppressor on the other.

12. Summary and Conclusions

The main aim of the present study was to obtain a detailed parametric characterisation of the suppression of a click-evoked OAE by an additional click. Past descriptions of this phenomenon have been limited in scope, and have yielded somewhat discrepant findings.

One of the key original findings of the present study is that the maximum suppression of a test click-evoked CEOAE generally occurs when a suppressor click is presented some milliseconds in *advance* of the test click, rather than for synchronous test and suppressor clicks. Although this finding has not been reported by any of the previous authors investigating the phenomenon, it represents a robust observation in the present data. It is likely that the apparent discrepancy between this and previous studies results from the more limited range of parameters, poorer sensitivity of the experimental measures and/or assumptions of the measurement techniques used in the previous work.

The test-to-suppressor click interval at which maximum suppression occurs is also found to exhibit a systematic dependence upon the levels of the two clicks. This interval is strongly dependent upon the level of the suppressor click relative to the test click, reducing towards zero as this level difference increases. The test-to-suppressor interval for maximum suppression also reduces, but less strikingly, as the levels of *both* test and suppressor clicks are increased together.

The present study also reveals that while the magnitude of suppression is predominantly dictated by the level of the suppressor click relative to the test click, it is also significantly dependent upon the level of the test click alone (for a fixed click-level difference). This latter relationship is non-monotonic, with suppression initially increasing with the level of the test click, but reducing at the highest levels of test click used. The predominant click level effect on the magnitude of suppression, i.e. suppressor click level relative to test click level, is also weaker at the highest test click level.

Further findings of the present study that were unreported by (or that differ from those of) previous authors result from the detailed examination in this study of suppression within restricted segments of the CEOAE waveforms. These include the finding that the key features described in the preceding paragraphs, relating to the inter-click interval giving maximum suppression, do not vary with waveform latency. Furthermore, while the amount of suppression does not vary with waveform latency for suppressors that lead the test click, it systematically increases with waveform latency for following suppressors. Suppression due to a following suppressor is also found to be far less sensitive to the dominant influence on suppression due to a leading suppressor of the level of the suppressor click relative to that of the test click. Although this is in direct contrast to some previously reported data, the previous findings are likely to have been influenced by measurement noise.

The quantification of CEOAE amplitudes within restricted waveform segments also permitted the observation of clear enhancements, or increases in amplitude under the influence of following suppressors, but never for leading suppressors. Although

previous authors have reported enhancements for leading suppressors, those studies may have been compromised by errors in their measurement technique, which assumed a lack of suppression due to a suppressor click that followed a test click. It was further found in the present study that CEOAE enhancements were usually accompanied by local changes in the corresponding waveforms – these have not been previously reported.

Finally, the use of restricted waveform segments in the analyses permitted the observation of strong suppressive effects due to following suppressors at *all* inter-click intervals (up to a maximum of +12 ms) used in the present study. In contrast, previous work had suggested only weak effects, and at somewhat sporadic inter-click intervals, for following suppressors.

A further original investigation conducted as part of the present study involved a test of the polarity-sensitivity of the suppression phenomenon. It is shown here that the magnitude and pattern of suppression is insensitive to the polarities of the test and suppressor clicks, for both leading and following suppressors. This finding establishes the validity of comparing without qualification the results of the present study with those of previous authors, who had used a slightly different measurement paradigm. More importantly, this finding contradicts suggestions in the literature that a polarity-sensitivity of the phenomenon may either augment the amount of suppression observed, or lead to the changes observed in the waveforms of CEOAEs recorded at high click rates. In addition, the finding of polarity insensitivity here suggests that the mechanism of click suppression is not simply related to CEOAE suppression due to continuous low-

frequency tones, as the latter phenomenon has been reported to exhibit a marked polarity dependence.

In obtaining a fuller and more detailed characterisation of click suppression than in previous studies, the present study also aimed to shed light on the mechanism underlying this nonlinear phenomenon. To that end, the relationship between click suppression and the marked compressive nonlinearity evident in CEOAE level functions was first investigated. A simple model of click suppression based solely upon level function nonlinearity was developed and the patterns of suppression generated by it were calculated. These patterns of suppression, specifically relating to the positions and magnitude of the maxima of suppression were a robust feature of suppression derived solely from level function nonlinearity, and were not affected by various modifications to the form of the model. However, a comparison of these simulated patterns of click suppression and the experimental data indicate that click suppression is not simply based upon CEOAE level function nonlinearity. Alternatives for the mechanism underlying click suppression were therefore considered.

It was firstly concluded that different mechanisms were likely to underpin suppression due to leading as opposed to following suppressors. In both cases however, the characteristics of the experimental data rule out either an (ipsilateral) efferent or a middle-ear reflex mechanism as the main source of the phenomenon. The main mechanism of click suppression as measured must therefore be entirely intracochlear.

It is hypothesised here that the major suppressive effects of a leading suppressor click are due to the disturbance of the CEOAE generator mechanism from its resting state,

prior to the elicitation of the test OAE. This may involve a type of biasing, involving the mechano-electrical activity of the OHCs. It is further hypothesised that the suppression generated is related to the envelope of the click response to the suppressor click, rather than to the instantaneous oscillatory response, due to the polarity insensitivity of the phenomenon and the relative smoothness of the suppression curves for small increments of inter-click interval. Under this general hypothesis the key features of these data, in relation to the inter-click interval at which maximum suppression is generated, are qualitatively consistent with direct measures of BM responses to click stimuli. The strong dependence of this inter-click interval upon the level of the suppressor click relative to that of the test click, and its weaker dependence upon the levels of both clicks, are consistent with the reductions in latency of the peaks of the envelopes of BM click responses, and of the onsets of these response, with increasing click level.

The most economical elaboration of the above hypothesis may involve a modification of the basic underlying I-O nonlinearity that gives rise to the compressive CEOAE level function. This may involve either a reduction of the gain or a shifting of the operating point of the I-O function. However, the present data do not permit the testing of these hypotheses: further research and more complex modelling studies are needed to assess them and other alternative explanations.

If the pattern of results obtained in this study may indeed be explained on the basis of the above hypotheses, it follows that such measurements may be used to probe the mechanics of the human cochlea to provide information complementary to that obtained by physiological measurements in other species.

In the case of suppression due to a following suppressor click, the data obtained in the present study do not refute the original hypothesis of a level-function-based mechanism. Although the experimental data exhibit a more complex pattern of suppression than that generated by the level-function-based model, this difference may be due to the fact that the true CEOAEs measured contain a complex (though possibly linearly-interacting) combination of components. As a following suppressor click occurs after the test click, it may differentially affect the intracochlear processes leading to the generation of these different CEOAE components. The simple model developed, in contrast, was restricted to simulations corresponding to a single frequency component and analogously, a single CEOAE generator channel. It is possible, therefore, that suppression due to a following suppressor does indeed reflect the basic CEOAE level function nonlinearity, but takes into account additional factors that are not represented in the model described in the present study. The finding that such suppression is strongly dependent upon the CEOAE waveform segment (in contrast with suppression due to a leading suppressor) is consistent with a fundamental link between the suppression due to a following suppressor and level function nonlinearity. Once again, more sophisticated modelling studies are required to address this issue.

Future experimental studies that utilise the techniques of the present work using tone burst rather than click stimuli may also be useful in refining and testing some of the hypotheses described above.

Other future studies that may fruitfully build on the work of the present study could include a detailed examination of CEOAE suppression due to a burst of noise rather than

an additional click, using the techniques described here. As described in Chapter 2 (Section 2.2.2), there is a difference of opinion amongst previous authors as to whether an entirely intracochlear or an efferent-mediated mechanism is involved in this type of suppression. However, none of the measurements reported to date have been conducted to the level of detail and measurement sensitivity as the work of the present study. An application of these techniques to noise burst suppression of CEOAEs may therefore yield new insights into that phenomenon.

Regardless of the exact mechanisms of click suppression, the phenomenon may provide a useful additional means of discriminating between nonlinear cochlear responses and linear artifacts in CEOAE measurements.

The data of the present study suggest that the mechanical response of the BM persists for as long as 24 ms or more – this is greater than suggested by most direct measures of BM click responses in laboratory animals. It is possible that direct physiological measures in laboratory animals tend to underestimate the duration of corresponding responses in the undamaged human cochlea.

The temporal extent of nonlinear interactions also suggests that the intracochlear disturbances associated with a CEOAE are highly nonlinear over the entire duration of the response. This suggests that the backward propagation of a CEOAE from the site of generation is itself either nonlinear or an extremely rapid process. The temporal extent of the effects seen in the present study may also call into question the assumption that non-simultaneous masking is not influenced by BM suppression.

A somewhat separate issue from those discussed above was addressed in Experiment Two of the present study. This related to the degree to which the suppression due to suppressor clicks presented individually accumulated in a simple, additive, manner when more than one suppressor click was presented. Such an additivity of suppression, in particular that due to leading suppressor clicks, had been hypothesised by previous authors. It was suggested that this accumulation of suppression could account for the greater magnitude of MLS rate suppression (seen when recording CEOAEs using streams of clicks at high click rates) as compared to the click suppression observed using a single suppressor and a single test click. However, no experimental data on the effects of multiple suppressor clicks on a single test click, which would permit a test of the above hypothesis, have yet been reported. Further, it was argued in the present work that the likelihood of nonlinear interactions between the multiple suppressors themselves may act *against* a simple additive accumulation of suppression. Data were therefore obtained in Experiment Two of the present study that compared the suppression due to a pair of a suppressor clicks to the suppression due to each click individually, with a primary focus on the effects of leading suppressor clicks.

The hypothesis of a simple accumulation of suppression may be more specifically formulated to imply that the net suppression due to a pair of suppressor clicks would exceed the suppression due to either suppressor individually, i.e. would exceed the suppression due to the more effective of the individual suppressors. In fact it is found here that for all combinations of leading suppressor clicks employed, the net suppression due to a pair of suppressors is always significantly *less* than that due to the more effective suppressor on its own. It is therefore concluded that the suppression due to leading suppressor clicks does not accumulate in a simple additive manner, as has been

hypothesised in the literature. Rather, the net suppression must be significantly influenced by additional nonlinear interactions between the multiple suppressors themselves, or by changes in the nonlinear interactions between each suppressor and the test click, in the presence of the other suppressor click.

A slightly more complex model of the net suppression due to multiple leading suppressors was therefore developed, in which a simple additive accumulation was modified by a reduction in suppression due to the action of one suppressor upon the other. It was argued that this reduction or “shortfall” in suppression for a pair of suppressors at a given inter-suppressor interval would be related to the amount of suppression due to a *single* suppressor click at the same interval (relative to the test click).

This model of the accumulation of suppression was examined by testing for a relationship across subjects between the above shortfall as experimentally determined, and the suppression measured for a single suppressor click at a corresponding inter-click interval. However, excluding the condition in which the shortfall in suppression and the single-suppressor suppression are mathematically related (due to the combinations of inter-click intervals involved), no significant relationship between these two variables is found. It is therefore concluded that the model of accumulation of click suppression, in which a simple additivity of single-suppressor effects is modified by the inter-suppressor interactions as described, is not adequate to explain the experimental data. Thus, either these inter-suppressor effects are not related to suppressor-test interactions at corresponding inter-click intervals as postulated, or the suppressor-test interactions are themselves significantly modified by the presence of a second suppressor click.

Although an additive accumulation of the effects of following suppressor clicks is not likely to account for MLS rate suppression, and the effects of following suppressors are seen to be more complex than those of leading suppressors, it was of some interest also to examine the accumulation of suppression due to following suppressors in this study. As the effects of different following suppressor clicks can be in different segments of the test-evoked CEOAE waveform, some degree of accumulation may have been expected here when considering the whole CEOAE waveform.

However, the results obtained here show that, as for leading suppressors, the suppression due to individual following suppressors does not uniformly accumulate. In most cases, the net suppression due to a pair of following suppressors is not significantly different from that due to the more effective suppressor individually. In two of the six conditions examined, further, this net suppression is significantly less than that due to the more effective suppressor. The more complex pattern of suppression seen for single following suppressors as compared to single leading ones is also reflected in these multiple suppressor measurements. For example, instances are observed of appreciable CEOAE enhancement when the suppressors are presented jointly, even though no enhancements are observed for either suppressor individually.

Finally, the accumulation of suppression due to one leading and one following suppressor (i.e., “mixed” suppressors) was examined. It was reasoned that a simple accumulation may be most likely in such cases, as the suppressor clicks themselves are maximally separated and are thereby likely to interact minimally with each other. Indeed, the data obtained here do indicate an increased tendency towards a simple

accumulation of suppression, over that observed for either leading or following pairs of suppressors. However, this finding is only statistically significant for one of the six combinations of mixed suppressors used. Nonetheless, the contrary finding of the net suppression being significantly *less* than that due to the more effective suppressor is never observed for mixed suppressors.

If the suppression due to mixed suppressors does indeed accumulate in a simple manner, then it may be such accumulation, rather than an accumulation of leading suppressor effects, that results in the greater magnitude of MLS rate suppression as compared to single-suppressor click suppression. Further work involving more detailed measures of suppression accumulation and corresponding measures of MLS rate suppression is required to investigate this possibility further. A careful quantification of the measurement noise floors in both types of measurements would also be important, as these may well limit the amount of suppression measurable and the MLS technique typically benefits from a substantially lower noise floor than click suppression measurements techniques.

The present study has revealed new information on a number of aspects of nonlinear temporal interactions in CEOAEs. Perhaps the most important of these is that these interactions, due to temporally separate click stimuli, are not simply a reflection of the compressive nonlinearity of the CEOAE level function, combined with a non-zero duration of the responses to these stimuli. It is hypothesised, instead, that the predominant nonlinear interactions are related to a biasing of the CEOAE generator processes by the envelope of the BM disturbance due to a preceding click. Further

experimental and modelling studies are needed to refine or reject this and other hypotheses that arise from the present work.

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Appendix I – Click cancellation artifact due to transducer “memory”

Chapter 3 (Section 3.1.2) referred to a small measurement artifact due to imperfect cancellation of the suppressor clicks, which was encountered in applying the test paradigm of the present study (illustrated in Figure 3.1) to the original POEMS system hardware used. This problem and its solution are described in more detail here.

Figure AI.1 shows a pair of replicate waveforms recorded using the basic test paradigm and the original system hardware with the ear-canal probe inserted into a 0.5 cc cavity. Test and suppressor clicks were both at a level of 70 dB pe SPL, the maximum click levels to be used in the main experiments, in order to generate the maximum amplitude artifact for illustrative purposes. A highly repeatable suppressor non-cancellation artifact of peak-to-peak amplitude of approximately 500 μ Pa is evident in the traces at about 10 ms. Note that the click amplitudes as recorded in the same traces (not shown in these plots) had peak-to-peak amplitudes of the order of 500 mPa – the non-cancellation artifacts here are therefore approximately 60 dB smaller than the original clicks. This artifact was also evident (though somewhat smaller) in the CEOAE waveforms obtained from ear-canal recordings, particularly for lower amplitude CEOAEs.

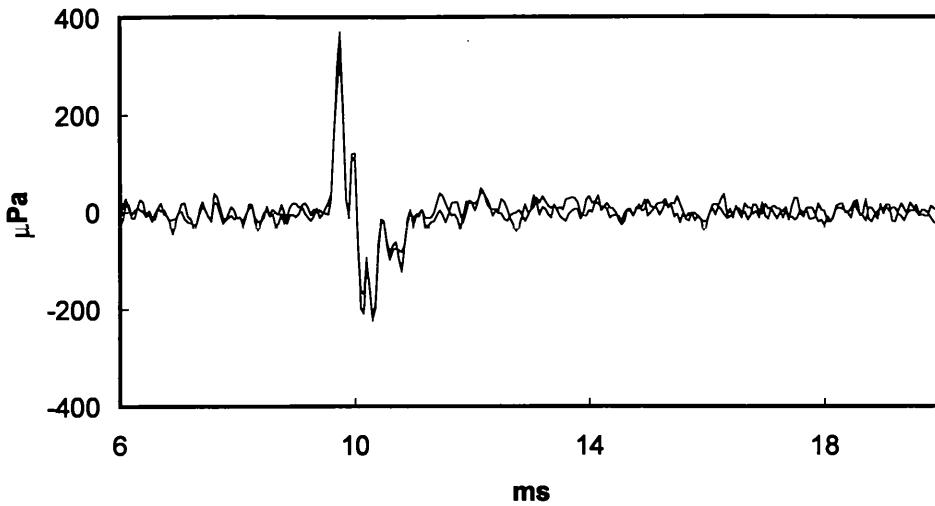


Figure AI.1. Replicate recordings obtained in a dummy cavity using the basic cancellation paradigm of the present study and the original system hardware. $L_S = L_T = 70$ dB pe SPL, $\Delta t = +9$ ms.

The artifact was not observed if the electrical click stream was coupled directly back to the measurement system input amplifier, indicating that it arose from the electroacoustic transducer section. Furthermore, similar artifacts were observed when the clicks delivered into a cavity were measured using a separate reference microphone, rather than the microphone housed in the probe itself, indicating that they arose from the output transducer (receiver) in the probe.

The stimulus signals delivered to the receiver were modified in a variety of manners, none of which eliminated the suppressor artifact. These included:

- (i) Adding and varying the DC bias to the receiver signal.

- (ii) Altering the duration of the electrical clicks delivered. (The click amplitudes were adjusted to compensate for this, in order to preserve the acoustic click amplitudes.)
- (iii) Utilising more complex eight-click sequences in the cancellation paradigm, rather than the basic four-click sequence illustrated in Figure 3.1.

However, it was noted that the artifact disappeared if the test clicks were not included in the presentation sequence – the suppressor clicks now cancelled completely into the noise floor. It appeared therefore, that the artifact was caused by the presentation of the test click prior to each suppressor click. Surprisingly however, the artifacts were completely *insensitive* to the test-suppressor interval, Δt . The significant feature of the preceding test clicks seemed rather to be that they alternated in polarity. In other words suppressor clicks of slightly different amplitudes were obtained if they were preceded by positive as opposed to negative test clicks, irrespective of the interval between these test and suppressor clicks. There therefore appeared to be a transducer “memory” of the polarity of the test click that did not reduce with time. As the receiver used operates on an electromagnetic principle, it seemed likely that magnetic hysteresis left it in a different resting state following a positive as opposed to a negative test click.

Tests were therefore conducted using a pair of similar transducers (in different probes), to separately deliver the test and the suppressor clicks into a reference cavity. This was expected to remove the hypothesised source of the artifact: as all suppressor clicks were positive, the resting state of the “suppressor” transducer would be the same, at the time of delivery of each suppressor click. These tests also necessitated a modification of the test system as a whole to utilise a second output channel from the CED 1401plus. No

non-cancellation artifacts were observed, consistent with the explanations for the effects described above. A modified POEMS probe that housed a pair of receivers was therefore constructed and used with a dual-channel output system to deliver test and suppressor clicks separately, as mentioned in Section 3.1.2.

A pair of replicate recordings using this modified “dual-clicker” probe, under exactly the same conditions as for the single-clicker waveforms presented in Figure AI.1 above, are shown in Figure AI.2. It is clear from the figure that any residual non-cancellation artifact, if present, is below the measurement noise floor.

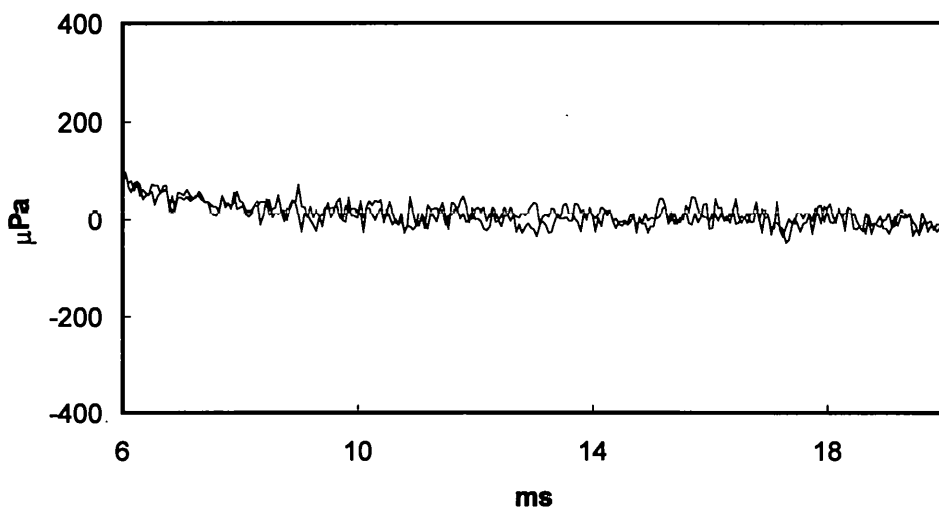


Figure AI.2. Replicate recordings obtained in a dummy cavity using the basic cancellation paradigm of the present study and the modified (dual-channel) system hardware. $L_S = L_T = 70$ dB pe SPL, $\Delta t = +9$ ms.

Discussions with the manufacturer of the receivers used have confirmed the likelihood of a residual magnetisation effect arising from hysteresis as being responsible for the artifacts observed.

It is therefore likely that such effects would also be present in some other systems used to make similar recordings, although they do not appear to have been identified in past literature on CEOAEs. In particular, as discussed in Section 3.1.2, it may be that the artifacts observed by Picton *et al.* (1993) when using bipolar MLS sequences originated from the same source: these authors also used a probe with a single receiver, made by the same manufacturer. Furthermore, it is well-recognised that the “on-line” DNL technique that is widely used in conventional CEOAE measurements (Section 2.1) is also subject to a stimulus non-cancellation artifact, particularly at high click levels.²⁸ Once again, a single transducer, with the same manufacturer as that used in the present study, is generally used to deliver clicks of variable polarity, and it is likely that the magnetic hysteresis effects discussed here contribute to this stimulus artifact.

²⁸ The artifact is of less consequence in conventional measurements than in the present study, as it does not impinge upon the main region of interest of the CEOAE recorded.

Appendix II – Generation of waveform segment RMS values from

1-ms slice units

As described in Chapter 3 (Section 3.3.1), signal and noise RMS values for each replicate pair of CEOAE waveforms were initially calculated in 1-ms time slices from the raw data, using the DADiSP signal analysis package. These 1-ms slice values were then all transferred to a single SPSS file for grouped and statistical analyses. This approach allowed for the calculation of measures such as suppression and suppression ceilings in arbitrary waveform segments within SPSS (provided all such segments fell on 1-ms boundaries), without necessitating repeated analyses of the original waveforms for each waveform segment. To do so, the RMS value of the desired waveform segment was calculated as the RMS of the individual RMS values of the 1-ms slices that made up that segment.

It is shown here that the RMS value of a signal so calculated from the RMS values of individual time slices is equal to that calculated directly from the original time waveform, provided the individual time slices are all of equal length.

Consider a (discrete) time signal (or segment of a signal) X , consisting of n points, i.e.

$$X = x_1, x_2, \dots, x_n$$

Let X also be composed of m contiguous time slices, denoted X_1, X_2, \dots, X_m , each of length k , i.e.

$$X_1 = x_1, x_2, \dots, x_k$$

$$X_2 = x_{k+1}, x_{k+2}, \dots, x_{2k}$$

$$X_j = x_{(j-1)k+1}, x_{(j-1)k+2}, \dots, x_{jk}$$

Then the RMS value of the signal X , as calculated from the original waveform, is

$$\text{RMS}(X) = \sqrt{\frac{1}{n} \sum_{i=1}^n x_i^2}$$

The RMS value of the j 'th time slice is

$$\text{RMS}(X_j) = \sqrt{\frac{1}{k} \sum_{i=(j-1)k+1}^{jk} x_i^2}$$

Therefore the RMS of the individual RMS values of slices X_1 through to X_m is

$$\text{RMS}(\text{RMS}(X_1), \text{RMS}(X_2), \dots, \text{RMS}(X_m)) = \sqrt{\frac{1}{m} \sum_{j=1}^m (\text{RMS}(X_j))^2}$$

$$= \sqrt{\frac{1}{m} \sum_{j=1}^m \left(\frac{1}{k} \sum_{i=(j-1)k+1}^{jk} x_i^2 \right)}$$

$$= \sqrt{\frac{1}{mk} \sum_{j=1}^m \sum_{i=(j-1)k+1}^{jk} x_i^2}$$

$$= \sqrt{\frac{1}{mk} \sum_{i=1}^{mk} x_i^2}$$

$$= \sqrt{\frac{1}{n} \sum_{i=1}^n x_i^2} = \text{RMS}(X) \quad (\text{as, by definition, } n = mk)$$

It is thus demonstrated that if an arbitrary segment of a signal waveform is divided into smaller time slices of equal length, the RMS value of the segment is equal to the RMS of the RMS values of these slices.

Appendix III – Relationship between “suppression” at $\Delta t = 0$ and $L_S = L_T$ and level function slope

It was shown in Chapter 4 that the suppression as measured by the measurement paradigm of the present study for the special case of synchronous and equilevel test and suppressor clicks ($\Delta t = 0$, $L_S = L_T$) arises entirely out of the compressive CEOAE level function. The quantitative relationship between suppression in this particular condition and the slope of the level function is derived here.

Figure AIII.1 shows an arbitrary level function, with a constant slope of m dB/dB. The output for a single input denoted x_1 dB is denoted y_1 dB, and the point (x_1, y_1) in Figure AIII.1 represents the *no-suppressor* input and output.

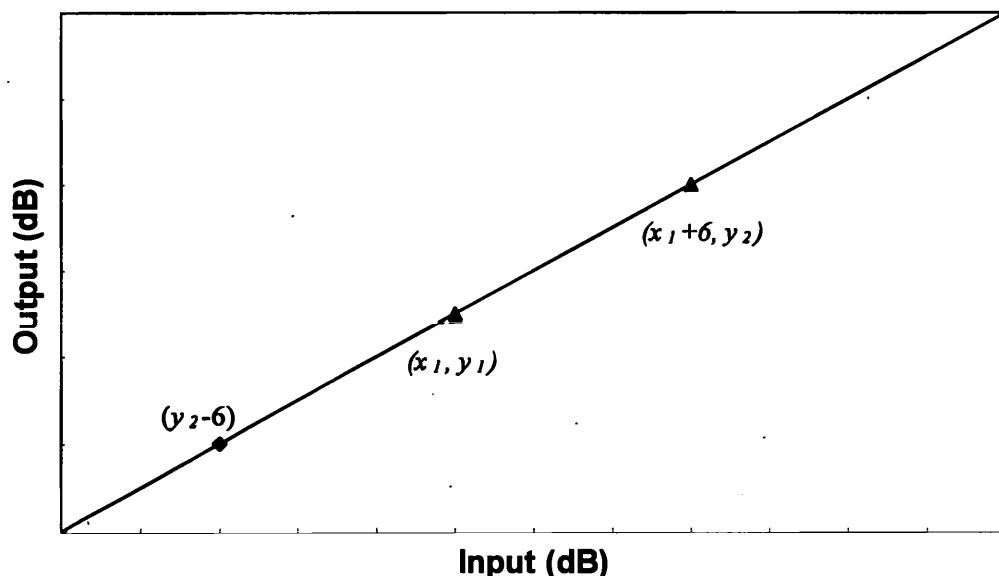


Figure AIII.1. Arbitrary level function with a fixed slope m dB/dB.

As discussed in Chapter 4, presenting an equilevel, synchronous suppressor along with the test click results simply in a doubling of the test click amplitude in one epoch of the averaging paradigm, and a cancellation of the test and suppressor clicks in the second epoch (see Figure 4.1). This doubling of test click amplitude corresponds to an increase in the input by 6 dB, and referring once again to Figure AIII.1, the output in this condition is denoted y_2 . Finally, the averaging of this output with that obtained in the second epoch (no signal) results in a halving of the measured signal: this averaged output for the *suppressor* condition is indicated in Figure AIII.1 as $(y_2 - 6)$ dB.

Suppression as defined in this study is the ratio between the output in the *no-suppressor* condition, to that in the *suppressor* condition, expressed in dB, i.e.

$$supp = y_1 - (y_2 - 6) = y_1 - y_2 + 6$$

Further, referring once again to Figure AIII.1, the slope of the level function,

$$m = (y_2 - y_1)/(x_1 + 6 - x_1) = (y_2 - y_1)/6$$

$$\text{i.e. } y_2 - y_1 = 6m$$

Therefore, $supp = -6m + 6 = 6(1 - m)$ dB

Note that in actual calculations involving the above relationship the more precise figure corresponding to an amplitude doubling of 6.02 dB was used, as stated in Equation 4.1.

Appendix IV – Glossary of abbreviations

ART	acoustic reflex threshold
BM	basilar membrane
CEOAE	click-evoked otoacoustic emission
Δt	time interval from test click to suppressor click
daPa	decapascals
dB	decibels
DC	direct current
DNL	derived nonlinear
DPOAE	distortion product otoacoustic emission
FIR	finite impulse response
HL	hearing level
HTL	hearing threshold level
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronic Engineers
IHC	inner hair cell
I-O	input-output
kHz	kilohertz
L_T	level of test click
L_S	level of suppressor click
μPa	micropascals
MEP	middle-ear pressure
MLS	maximum length sequence
mPa	millipascals

MPP	masking period pattern
ms	millisecond
OAE	otoacoustic emission
OHC	outer hair cell
pe	peak-equivalent
POEMS	Programmable Otoacoustic Emission Measurement System
RMS	root mean square
S	suppressor click
s	second
SD	standard deviation
SFOAE	stimulus frequency otoacoustic emission
SL	sensation level
SOAE	spontaneous otoacoustic emission
SPL	sound pressure level (dB SPL \equiv dB re 20 μ Pa)
SSOAE	synchronised spontaneous otoacoustic emission
supp	suppression
T	test click
TBOAE	tone burst-evoked otoacoustic emission
TEOAE	transient-evoked otoacoustic emission